Project Status Report

US Collaboration

for the

Compact Muon Solenoid (CMS) Detector

October 15, 1996

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US Collaboration for the
CMS Detector
at the CERN LHC

Abstract

We propose to participate in the building of the Compact Muon Solenoid (CMS) experiment which is designed to study the collisions of protons on protons at a center of mass energy of $\sqrt{s} = 14$ TeV at the Large Hadron Collider (LHC) at CERN. In order to enable studies of rare phenomena at the TeV scale, the LHC is designed to operate at a luminosity of 10^{34} cm^{-2} s^{-1}. The physics program includes the study of electroweak symmetry breaking, investigation of the properties of the top quark, searches for new heavy gauge bosons, probing quark and lepton substructure, looking for supersymmetry and exploring for other new phenomena.

We propose to take leadership responsibility in the CMS experiment for the endcap muon system including the chambers, steel design and integration, and for all hadron calorimetry, as well as associated aspects of the trigger and data acquisition system. We also propose to work on important areas of electromagnetic calorimetry, tracking, and software.

This document first provides details of the US CMS Collaboration FY 1997 funding requests to DOE and NSF. The requests are presented in the context of the completed FY 1996 activities, the CMS schedule and milestones, and the management and construction responsibilities of the US CMS groups. Both R&D and travel funds are requested to sustain US CMS activities during the period prior to the anticipated FY 1998 project funding. The FY 1997 funding request is $4620K from DOE and $782K from NSF. In addition, $300K in supplemental university travel funding is requested from DOE.

In addition, high level negotiations between DOE and NSF on one side and CERN on the other have reached an agreement in principle. This agreement has lead to fiscal guidance given to US CMS by DOE and NSF. That guidance entails both a total project cost and a tentative project funding profile. This document responds to our guidance by presenting a full revised level 5 WBS for the US CMS project. In addition, a first cost profile has been completed.

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1 Introduction

The US CMS project has been given a detailed exposition in the US CMS Letter of Intent (LOI) [1]. That construction project represents at present the aspirations of 324 physicists from 40 US institutions.

This document first gives the US CMS FY 1997 proposal. A separate document gives more detail for the NSF requests [2]. We concentrate on the requests for FY'97 to both DOE and NSF in the light of the completed FY'96 activities and the long range schedule.

A summary of the major milestones appears in Section 2 of this document and in Annex 9 of the CMS Interim Memorandum of Understanding (IMOU) [3]. The schedule for CMS from now until the initial run of CMS in 2005 appears in Fig. 1. With CMS, the US CMS responsibilities are spelled out in board terms in the IMOU. A short version of the participation of US CMS groups in the subsystems of the detector appears in Table 1. It is within the context of the schedules, milestones and responsibilities of the US groups that the FY'97 request is made. The participation of the US CMS groups in the R&D, prototyping, and construction efforts of the CMS detector subsystems appears in summary in Annex 6 of the IMOU [3]. The FY'96 R&D efforts by subsystem and the FY'97 requests are given in Section 3 in some detail.

The supplemental travel request for US CMS appears in Section 4. These funds are used in support of DOE university groups in their activities specific to US CMS in FY'97.

A summary of the level of support required to sustain these activities in FY'97 is given in Table 2. The labor cost estimates shown include institutional overhead charges. A detailed breakdown of the activities, the deliverables, the associated costs and the participating groups is given in Section 3 of this document on a subsystem by subsystem basis. Also shown in Table 2 is a summary of the supplemental travel support requested of DOE. The context of the requested travel support is included in Section 3, and details are provided in Section 4. We note that the requested level of funding is the minimum necessary to sustain the US groups in their ongoing activities. A summary of the requested FY 1997 support by institution is given in the Addendum at the end of this document.

Given where the US CMS Collaboration is in FY'96, and where it is going, the request for FY'97 occurs within a well defined framework. The US CMS groups are wholly responsible for building the endcap muon detectors, for designing the endcap steel return yoke, for building the barrel and half the very forward hadron calorimeter, and for constructing the related muon and calorimeter level 1 trigger systems. In addition, US CMS groups are responsible for major and coherent efforts within the other subsystems. Within the electromagnetic calorimeter, we are responsible for APD evaluation, front-end electronics R&D, and crystal characterization. Within the tracking system, US groups are wholly responsible for the forward silicon pixels. In the area of software and computing we naturally lead in detector performance modeling for the EMU and HCAL systems.

The recent successful completion of negotiations between DOE/NSF and CERN has resulted in a total US project cost for LHC detectors of \$250 M in then-year or "as-spent" dollars from DOE, and \$81 M in FY 1995 dollars from NSF. Given funding profiles from DOE and NSF, economic escalation indices for DOE Construction Projects, and the assertion that the funding is to be split equally among the two experiments, the US CMS Total Project Cost is approximately $173 M in then-year dollars. In response to this fiscal guidance, the US CMS collaboration has designed the scope of the US CMS project to this cost from the bottom up. We have assumed that M&S costs are without overhead. Labor and EDIA salary charges are fully encumbered rates at the institutions assigned to do the work. The contingency analysis is done at level 5, or lower, of the WBS and follows standard DOE procedures. The analysis and WBS presented in Section 5 of this document is done in this year, FY'96, dollars. Project management (representing incremental overhead) is explicitly broken out as a distinct cost.

The WBS at level 5 has distinct deliverables labeled by the name of the responsible party. That party may be a non-US collaborator, base program resources (where identified), or a specific funding agency – NSF or DOE. The specific NSF items are broken out and shown in Section 6; which summarizes the recent US CMS proposals to NSF [2].

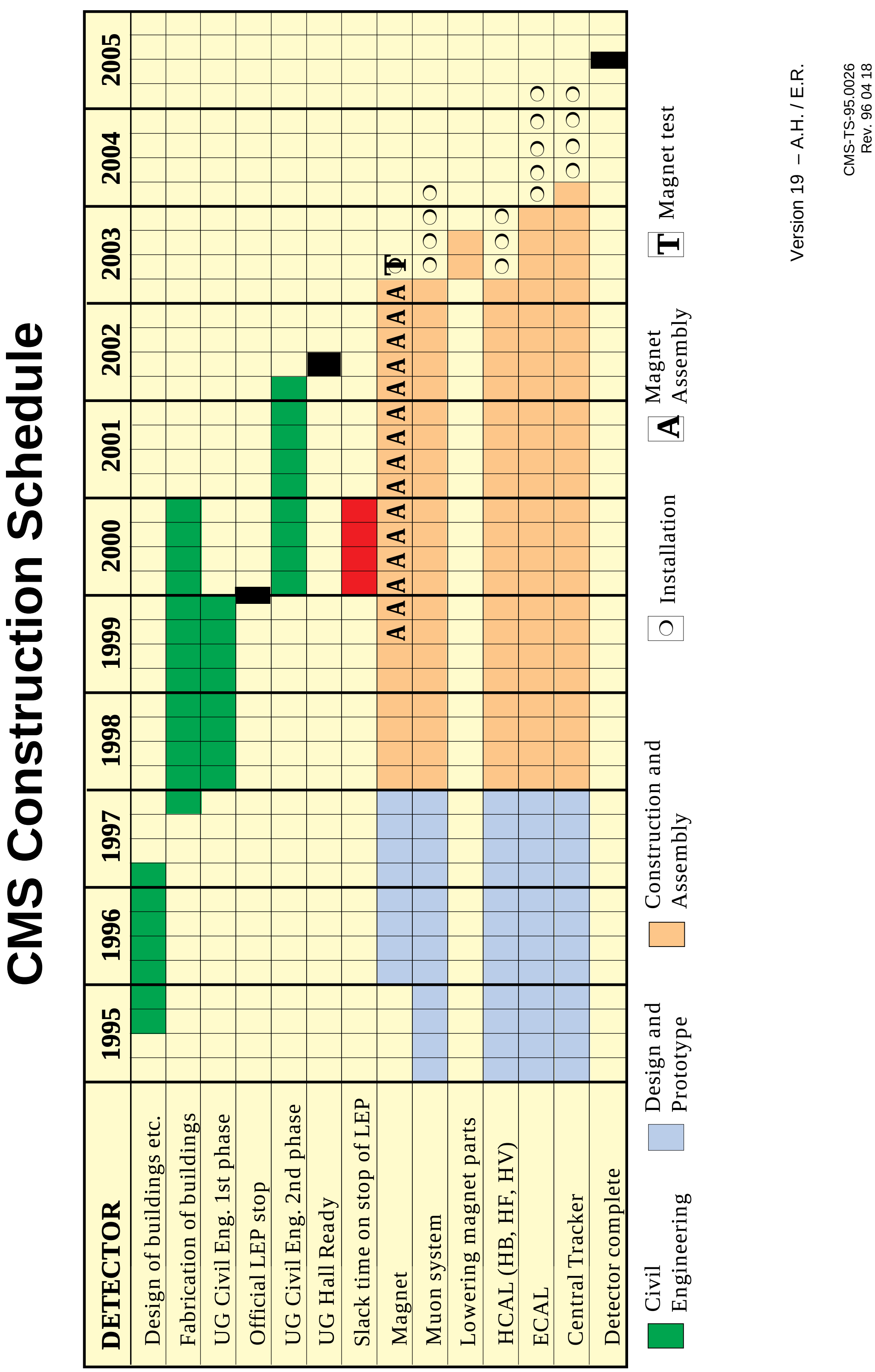


Figure 1: CMS construction schedule: 1995 to 2005.

Table 1: US CMS Subsystem Participation.

Endcap Muon	HCAL	Trigger/DAQ
Alabama	Boston	UC Davis
UC Davis	UCLA	UCLA
UCLA	Fairfield	UC San Diego
UC Riverside	Fermilab	Fermilab
Carnegie Mellon	Florida State	Iowa
Fermilab	Illinois Chicago	Iowa State
Florida	Iowa	MIT
Livermore	Iowa State	Mississippi
MIT	Maryland	Nebraska
SUNY Stony Brook	Minnesota	Northeastern
Northeastern	Mississippi	Ohio State
Ohio State	Notre Dame	Rice
Purdue	Purdue	Wisconsin
Rice	Rochester	
UT Dallas	Texas Tech	
Wisconsin	Virginia Tech	

ECAL	Tracking	Software
Brookhaven	UC Davis	UC Davis
Caltech	Fermilab	UCLA
Fermilab	Florida State (SCRI)	UC Riverside
Livermore	Johns Hopkins	UC San Diego
Minnesota	Livermore	Caltech
Northeastern	Los Alamos	Carnegie Mellon
Princeton	Mississippi	Fermilab
	Northwestern	Florida
	Purdue	Florida State (SCRI)
	Rice	Johns Hopkins
	Texas Tech	Livermore
		Maryland
		Minnesota
		SUNY Stony Brook
		Northeastern
		Princeton
		Rice
		Wisconsin

Table 2: US CMS FY 1997 Funding Request (K$).

Subsystem/Activity Description	FY'97 Req. DOE	FY'97 Req. NSF	Travel DOE
US CMS FY 1997 Funding Request	**4620**	**782**	**300**
Endcap Muon Detector	**1503**	**83**	**75**
CSC Chambers	659		45
Electronics	520		
Steel Design and Integration	224		5
Trigger	60		5
Alignment		83	
RPC Chambers	40		
Endcap Management			20
Hadron Calorimeter	**1650**	**211**	**75**
Barrel HCAL:			
Optical System Design	105	95	21
Calibration System	115		10
Photodetectors	70		7
Electronics R&D	20		3
Preporduction Prototype	780	115	
Test Beam Motion Table	165		6
Engineering/TDR	175	1	10
Forward Calorimeter:			
QF Engineering	25		7
QF preproduction prototype	20		3
QF Electronics	16		3
QF Test Beam	39		3
QF TDR	27		
QF Optics	11		2
QF Radiation Damage	5		
Test Beam Prototypes	77		
Trigger and Data Acquisition	**550**	**109**	**35**
Level 1 Calorimeter Trigger	250		6
Level 1 Muon Trigger	160		12
Luminosity Monitor		59	17
Data Acquisition	140	50	
Electromagnetic Calorimeter	**514**	**57**	**45**
Photodetectors	104	57	15
Electronics	200		15
Crystals	210		15
Tracking System	**293**	**130**	**35**
Pixel Tracker	293	130	35
Project Management	**110**	**192**	
Coordination and Planning	22		
Cost and Schedule Management	33		
Information Systems	23		
Administrative Support	32		
NSF Administration		192	
Software and Computing	**0**	**0**	**35**

2 CMS Milestones

The CMS project was defined by the submission of the technical proposal on December 15, 1994 [4]. Since that submission, the CMS collaboration has had a continuing dialogue with the CERN LHC Experiments Committee (LHCC) on the technical feasibility of the experiment. This dialogue has culminated in approval of the CMS experiment in regard to the science at the November 16, 1995 meeting of the LHCC.

This dialogue has also resulted in the establishment of milestones by joint consultation with the LHCC referees and the project managers of the CMS subsystems. These milestones, which define the steps which need to be accomplished if the CMS experiment is to maintain the schedule given in Section 1 of this document, are shown in Tables 3 to 9 below.

The implications for the US CMS groups follow from the responsibilities which they have taken in CMS. In particular, since the endcap steel yoke and the HCAL are critical path items, the engineering effort necessary to specify the design of the yoke and the barrel wedges must be done in FY'97. This is so because the technical design report for the magnet subsystem must be completed in 1996 in order to maintain the CMS schedule. For the HCAL, the bids for the wedge preproduction prototypes must be fully prepared in 1997 in order to stay to the schedule.

We note that the FY'97 level of funding will not allow US CMS to meet all the milestones given by CMS. This problem continues throughout the later years of the US CMS project and is more fully discussed in Section 5 of this document when cost profiles are developed for the full project duration and compared to the funding profile guidance given us by DOE and NSF.

Table 3: Muon System

Item	Completion
Technical Design Report	Dec 1997
Barrel Drift Tubes Chambers:	
Full size chamber (12 layers) meeting the performance requirement	Dec 1996
Final chamber suitable for mass production	Dec 1997
Electronics	
Front-End prototype (ampl. + discr. + driver)	Dec 1996
Meantimer and correlator final chip for full trigger test	Dec 1997
MF/1/1	
Fabrication and test of a final MF/1/1 large size prototype (6 layers)	Dec 1996
Preseries sample	Dec 1997
MF/1/2, MF/1/3, MF/2-4	
Full size large chamber (6 layers)	Dec 1996
Final chamber suitable for mass production	Dec 1997
Front-End cards for cathode and anodes	Dec 1997
RPCs	
Definition of detector parameters	Dec 1996
Final prototype suitable for mass production	Dec 1997
Final Front-End chips	June 1997
Alignment	
Full scale LINK system bench test	Dec 1996
Integrated design for LINK + BARREL + FWD	June 1997
Full scale system test	Dec 1997

Table 4: Hadron Calorimeter

Item	Completion
Technical design report	June 1997
Transducer and calibration final selection	Sep 1996
Engineering drawings available to request bids for HB and HF	Jan 1997
Preproduction prototypes (HB and HF)	Dec 1997

Table 5: Trigger and DAQ

Item	Completion
Trigger:	
Prototypes of the basic components of level 1 trigger	Dec 1996
Full chain trigger prototypes	Dec 1997
DAQ:	
DAQ basic unit prototypes (DPM, FED, Switch interfacing)	Dec 1996
Integration of event builder structures based on commercial switches	Dec 1997

Table 6: Electromagnetic Calorimeter

Item	Completion
Technical Design Report	Dec 1997
Crystals:	
Definition of specification for preproduction	Dec 1996
Preproduction	1997
Avalanche Photodiodes:	
Choice of final APD June	1997
ECAL prototype performance:	
100 Crystal matrix DE/E at 100 GeV 0.6% voltage- and temperature-stabilized	Dec 1996
Readout Electronics:	
Global test of the full readout chain with final very front-end	Dec 1997

Table 7: Tracking System

Item	Completion
Technical Design Report	Dec 1997
Pixel Detector:	
Prototype module with analogue block satisfying LHC requirements	Dec 1997
Decision on readout architecture	Dec 1997
Decision on detector material between Si and GaAs	Dec 1997
Electronics:	
Final decision on choice of optical technology	June 1996
Full readout chain operational	Dec 1997

Table 8: Solenoid Magnet and Return Yoke

Item	Completion
Technical Design Report (Coil + Yoke)	Oct 1996
Preliminary Design Review of Coil	Apr 1996
Contract for Barrel Yoke	June 1997

Table 9: Computing

Item	Completion
Technical Proposal for Computing	Dec 1996

3 Progress in FY 1996 and Plans for FY 1997

In this section we will present the progress made in FY'96 and our plans for FY'97. The pace which we have adopted for this program is determined by the schedule and milestones which we have to keep in order to build a working detector on time. This, in turn, dictates the funding requirements which are described in detail below.

Ten percent of the FY'97 R&D funds will be withheld as a management reserve to be distributed at mid-year, as outlined in the US CMS Project Management Plan [5]. The DOE reserve will reside in a no-overhead Service Account provided by Fermilab for that purpose; the NSF reserve will remain at Northeastern. The purpose of the management reserve is to provide US CMS with enough fiscal flexibility to make "mid course corrections" during the fiscal year.

3.1 Muon System

Detection of muons is of central importance in the CMS experiment since muons from p-p collisions will provide clean signatures for a wide variety of new physics processes. The task of the muon detector is to identify these muons and provide a precision measurement of their momenta from a few GeV to a few TeV. At the LHC, efficient detection of muons from Higgs, W and Z sources requires coverage over a large rapidity interval. The CMS muon system design has a barrel detector covering the central region out to $|\eta| < 1.3$ and an endcap detector, which overlaps the barrel in the region $0.9 < |\eta| < 1.3$ and provides standalone coverage for $1.3 < |\eta| < 2.4$. The endcap detector is the responsibility of the US groups.

3.1.1 Introduction

Four endcap muon stations MF1 through MF4 provide a minimum of three sets of measurements on a muon track outside the central solenoid volume [6]. Each station is made up of six layers of cathode strip chambers (CSC). The readout electronics must be capable of acquiring information from the CSCs, generating trigger primitives for the first-level trigger, and storing the information in a pipeline until the global first-level trigger decision is made. The muon trigger identifies muon track candidates with a transverse momentum threshold that can be varied as necessary to keep the trigger rate under control. At the same time, the trigger system must unambiguously identify the bunch crossing with high efficiency. The management structure for the muon system is shown in Fig. 2.

3.1.2 Endcap Muon Chambers

Accomplishments in FY'96 Chamber R&D of the last year was primarily concentrated in three major fields:

- tests of intrinsic chamber performance;

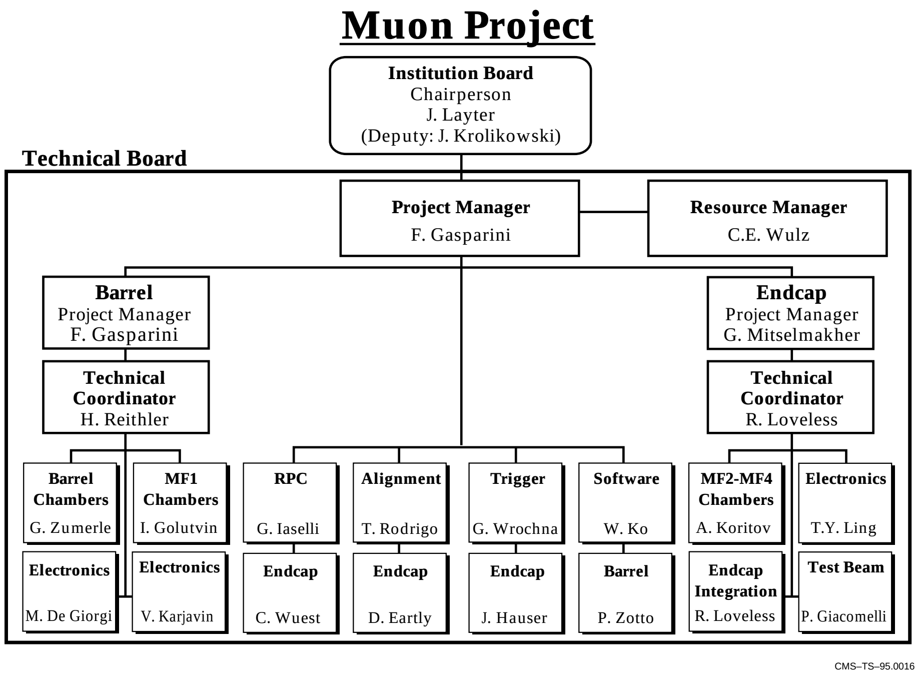


Figure 2: CMS Muon Project organization.

- optimization of large chamber design and building and testing prototypes to verify it;
- chamber production issues (cost, schedule, sites). This is discussed in Section 3.1.3.

Tests of Intrinsic Chamber Performance The six-plane 0.5×0.5 m^2 P0 prototype was built in 1995 by the West Coast collaborators and tested in a muon beam. During this past year a comprehensive study of the chamber calibration [7], spatial resolution, and timing capabilities was carried out. The P0 prototype had very wide strips (16 mm), representing the widest strips that will be encountered in the endcap system, at the outer radius of the largest chambers. For hits near the center of such strips, very little charge is shared, so the resolution varies rapidly across the strip. The data are shown in Fig. 3 and are seen to agree very well with the results of simulations. When six planes with staggered strips are combined together, the overall position resolution is about 40μm, which more than meets our goals. Also an efficiency of nearly 99% in generating a time stamp within a 20 ns window was measured in these tests, which satisfies our requirements.

The P0 prototype was modified and then tested in the muon beam again in August of 1996. This time it had narrower strips, 6 mm wide, to represent the narrowest strips of the final CMS chambers. Also, the wire spacing was significantly increased and thicker wires were used. Special electronics designed to test the concept of getting half-strip resolution at the first level trigger was used in these tests. The chamber resolution was found to be around 50 to 60 μm per plane (or around 30μm per chamber). The efficiency of getting the correct half strip was measured to be high, about 92%. This result is of vital importance for

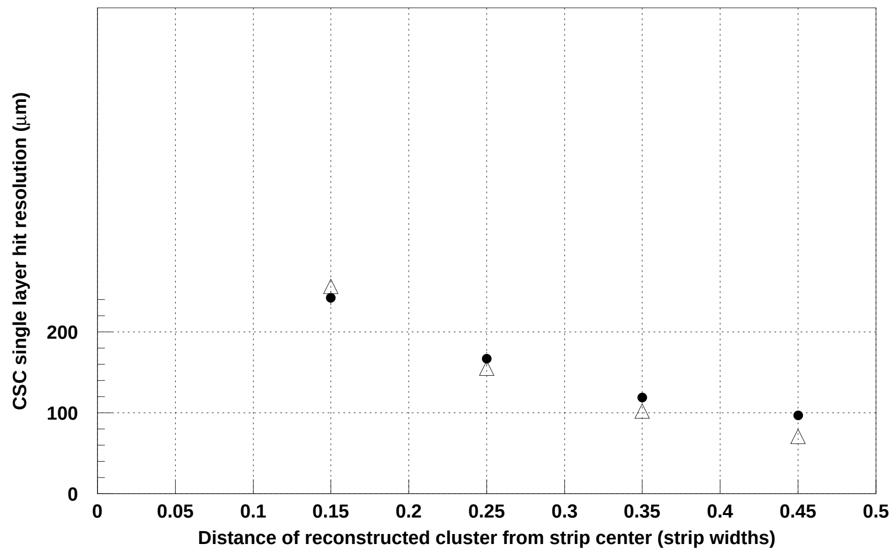


Figure 3: CSC resolution vs. distance from strip center for the P0 prototype compared with the simulation.

trigger simulations. The complete analysis of the very large data sample has just begun.

We have also built a setup for conducting aging tests on cathode strip chambers. A few small scale chambers have been built following the current baseline design with the baseline materials. They are operational and currently undergoing the aging tests.

Large chamber design and engineering prototypes The T1 engineering prototypes, each 1.6×0.6 m^2 with 2 gaps and 1.4 m long wires, were built at Fermilab during the past year, allowing us to test a number of new design ideas intended to simplify chamber construction, decrease cost, and improve reliability. The most significant improvements are the use of the following: commercially made cheap panels; strips milled directly on the panels; thicker and therefore stronger 50 μm wire from Sylvania; a new very efficient wire winding technique; wider wire spacing (lower HV and relaxed tolerances); no intermediate nylon lines to support anode wires a simple gas seal formed by liquid RTV; gap frames which were ground rather than machined to obtain the required tolerances more cheaply; HV segmentation within a single wire plane; simple guard strips rather guard wires. The T1 prototypes were thoroughly tested and showed very reliable performance.

All of the above features have been accepted in the design of the large scale P1 prototype which will have 6 gaps, and an area of 3.3×1.2 m^2. This will be the will be the largest cathode strip chamber ever built. Given this unprecedented scale, we have built and tested a two-layer version of this chamber, the P1A prototype, before proceeding with the six-layer version. The two-layer chamber's operation was very stable and gave us confidence in our design. We were able to study effects which only become apparent in large scale chambers, like temperature gradients and overpressure on panel bulging and gas gain uniformity over large areas. Also, the issue of proper grounding of multiple planes of very sensitive electronics channels has been thoroughly investigated. Based on the experience with P1A, we have slightly modified the design of P1 and are proceeding with its construction. The first test results are due in December of 1996. In order to make detailed performance studies of these large prototypes, we are building a cosmic ray setup of adequate dimensions. This project is still under way but has already allowed us to carry out the tests discussed above.

Design Status There is one major change in the overall chamber layout since last year: we have changed the 10 degree wide segmentation of chambers MF/2/1, MF/3/1, MF/4/1 to 20 degrees. This modification was made to decrease the number of chambers in those stations which, in turn, significantly reduced the cost of the project. It also resolved a space conflict at the bottom corners of these chambers. Since the number of readout channels remained approximately the same, this change has had almost no impact on the front-end electronics, and the trigger group has been able to accommodate this new geometry.

Otherwise, the basic chamber design remains essentially intact Many of the design features we tested in 1996 had been already adopted in late 1995 on the basis of careful analytical calculations and prior experience. The difference with respect to last year is that now, having built and tested several prototypes, we have confirmed the expected chamber performance and are much more confident in our design and cost-estimate.

Chamber Work in FY'97 In FY'97 we will concentrate our effort on six chamber R&D areas, these are:

1. the completion of the cosmic ray setup for testing the large scale prototypes;
2. testing of the P1 prototype;
3. the design and construction of the full scale chamber P2;
4. the design and prototyping of critical chamber production tooling;
5. performance studies with smaller chambers;
6. the preparation of the chamber production plan (sites, cost, schedule, sharing of responsibilities), discussed in Section 3.1.3

Cosmic Ray Setup As mentioned above, a cosmic ray setup of large enough to accommodate the largest chambers is now under construction at Fermilab. In this setup, scintillator counters covering the entire chamber area will provide a muon trigger, multi-hit TDCs, similar to those used for P0 prototypes, will permit chamber timing studies and a high-precision pulse generator will be used for calibrating the 384 channels of cathode electronics.

Tests of the P1 Prototype The P1 prototype construction and testing is the major chamber milestone in 1996. Since it is the size of the largest CMS muon chambers, the results from P1 will be of crucial importance for the entire muon project. These tests will involve a full program of performance studies, including spatial and time resolution, trigger patterns, efficiencies, etc. It is worth emphasizing once more that there is no previous experience with a chamber this size we could appeal to in specifying the expected chamber performance.

Design and Construction of the P2 Prototype P2 will be designed exactly as an MF/2/2 chamber rather than simply as a large scale CSC. This idea appears to be feasible now that we have settled on most of the chamber design features and on the overall system outline. A few design and construction features are expected to change as compared to the P1 chamber but they should not effect the performance. This prototype is the major milestone for 1997, and the first results are due in December of 1997.

Tooling Design and Prototyping We have taken the standpoint that the P2 prototype will be built with the machines and tools which we envision for the final production. There are a number of such devices which are critical and cannot be purchased off-the-shelf. Accordingly, we are proceeding with the design and construction of these machines, as we discuss in the following section, and the prototypes of these machines will then be used in the construction of the P2 chamber.

Performance studies As described earlier, in 1996 we have made all the necessary arrangements to start aging tests on the regular basis and the first results are expected to be presented in November. Given the importance of this issue, detailed studies of aging will continue for some time. Optimization of the gas mixture is closely related to these aging tests and chamber timing performance. These tests will be done with smaller chambers.

3.1.3 Endcap Muon Production Plan

The endcap muon production plan appears as Section 5.1.1 of this document, in the context of the US CMS Project.

3.1.4 Endcap Muon Electronics

Baseline Design of the Readout Electronics The front-end electronics for the endcap muon system performs two main tasks: 1) Record and send precise muon position and timing information to the data acquisition (DAQ) system; 2) Identify track segments in a CSC module as trigger primitives for the first level muon trigger. The electronics will be arranged as follows: sixteen neighboring cathode channels from each of the six chamber layers are connected to a cathode front-end board (FEB) mounted on the chamber. The anode channels, each of which is a gang of 10-20 wires, are arranged similarly. The readout and trigger data are sent from the cathode and anode FEBs to a Readout Motherboard which serve as the interface to DAQ and the global level 1 trigger.

The cathode FEB consists of 96 input channels per board. Each front-end board is designed to read out a tower consisting of 16 neighboring strips per layer by 6 layers deep. Each input pulse is sent to a low noise amplifier followed by a semi-gaussian shaper with tail cancellation. The shaping time is 100 ns. There are two output voltage pulses from each shaper. One of them is connected to the trigger path where time and spatial coincidences of cluster centroids from a minimum number of chamber layers are looked for and identified as local charged tracks (LCT). The time stamp, location and angle of the LCT are used to determine trigger primitive parameters for the level 1 muon trigger. The other output from the preamp/shaper is connected to a "precision" DAQ path where the voltage level is sampled every 50 ns and held in a Switched Capacitor Array (SCA) during the level 1 latency. The stored samples are digitized and read out into the DAQ when trigger conditions are satisfied.

The anode FEB also consists of 96 input channels per board. The amplifiers are optimized for timing instead of low noise. The signals are shaped with a shaping time of 30 ns and sent into constant fraction discriminators. The logic pulses from the discriminators are used to find anode LCT triggers and to determine their bunch crossing times. They are also latched and pipelined for DAQ readout, providing a crude measurement of the radial coordinate of the track segment.

Accomplishments in 1996

Cathode Preamp/Shaper ASIC Development The cathode preamp/shaper ASIC has gone through three submissions, each a four channel ASIC for engineering study. Submission 1 was sent to ORBIT, and the ASIC worked well except the noise substantially exceeded our specification. Measurements indicated that a large fraction of the noise originated from the shaper stage. This was corrected in submission 2, which went to ORBIT, and submission 3, which was sent to MOSIS-HP with linear capacitors. In both cases 1.2 μm CMOS technology was used. The ASICs have been delivered from both companies and have been bench tested. The measured gain of 0.45 mv/fC agrees well with SPICE simulation and the chip-to-chip variation in gain was less than 5%. The chips have a >5% deviation from linearity (0-2 volts), the source of which has been identified. The noise measurements indicated that the second stage noise had been significantly reduced compare to the first submission, and that the HP process is 50% less noisy than the ORBIT process and is close to our design goal. In mid-September we have submitted another 4-channel ASIC to MOSIS-HP. SPICE simulations shows that it should meet all our design specifications. Fig. 4 shows the expected deviation from linearity of the amplifier/shaper from 0-2 volts. This chip will be delivered to us in mid-November.

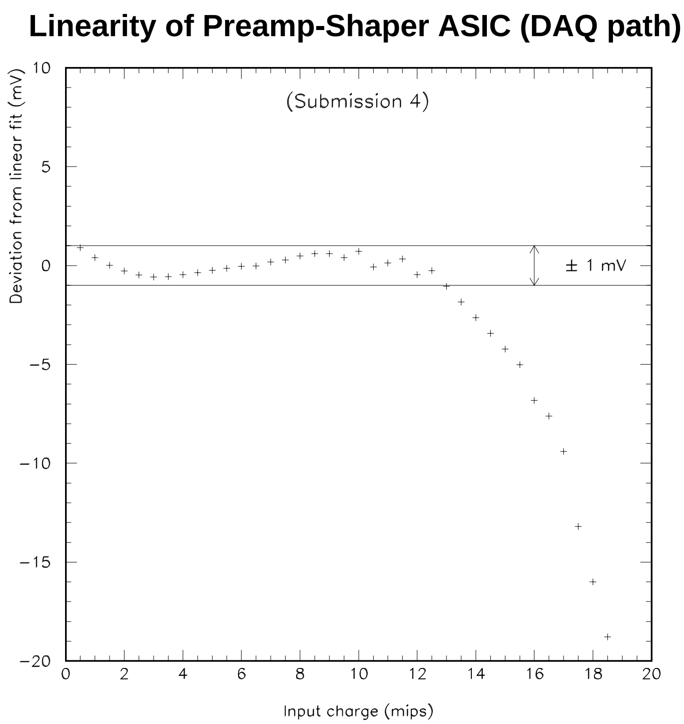


Figure 4: Deviation from linearity as a function of the input charge for preamp/shaper ASIC submission 4. The result is obtained from a SPICE simulation. The output pulse height for 1 mip input charge is 100 mv.

Switched Capacitor Array ASIC Development The main progress in SCA is the reduction of cell-to-cell pedestal variation. It was found to be correlated with cell addressing. Simulation showed that the pedestal variation could be reduced by adding inverters to each Gate Driver. This design change was implemented on SCA-2B, a 3-channel by 28 capacitor engineering ASIC submitted in May [8]. The bench test of SCA-2B was completed which shows that cell-to-cell pedestal variation is ≤2mv peak-to-peak, about a factor of six improvement over the previous chip (SCA-2A). The design of the full-size 16-channel by 96-capacitor ASIC was completed and the first iteration will be available for testing in November.

Cathode Readout Controller ASIC Development The function of the readout controller is to generate write and read addresses for the SCA. The conceptual design of the controller is finalized. The main component in the design is an addressing scheme which uses a Gray Code sequence. The 96 addresses are divided into 16 blocks. Blocks in use are tagged, and the tag is lifted when there is no local or global trigger after fixed delays. This scheme has been simulated, and the logic is implemented for FPGA (XILINX). We are in the process of synthesizing the logic into a downloadable file. Timing and efficiency of block usage will be studied. A test board has been built to exercise a simpler version of this scheme using a sample SCA-2A ASIC.

Cathode 96-channel PC Board The preliminary layout of the DAQ part of a full 96-ch cathode FEB has been made. This layout will evolve into a prototype PC board which will contain full size ASICs for bench test and on-chamber tests next year.

Anode Preamp/Shaper ASIC Development The first round 4 ch-ASIC for the preamp/shaper was submitted to ORBIT in July and was delivered at the end of August. The design specifications are: semi-gaussian with tail cancellation; 30-50 ns shaping time; 5 mv/fC gain; <10% deviation from linearity from 0-0.5v; 0.4 fC noise at 0 pF and 1.7 fC at 200 pF. The bench test of this ASIC will start soon.

Anode Discriminator ASIC Development The first round 4-channel ASIC was submitted in August. The design contains two discriminators: a high threshold discriminator driven by the amplified pulse whose output is used as "enable", and a low threshold discriminator driven by a constant-fraction shaped pulse for precise timing. The high threshold is adjustable from 20 to 500 mv. Simulation shows that slewing of the output pulse is 2 ns. This chip will be delivered and tested in October.

Plans for 1997 The key milestone to be met at the end of 1997 is the production of a pilot readout electronics system which contains prototypes for the DAQ readout part (excluding trigger) of the cathode and anode 96-channel pc boards. In most cases, the ASICs used on these boards will be preproduction samples which should be as close to the final version as possible. The performance of this pilot system will be tested on a 6 layer CSC prototype chamber (P1 or P2). Issues related to cables, connectors, RF shielding and cooling will also be investigated with this system. The goals to be achieved in 1997 to meet this milestone are summarized below.

1. **Finish development of the Cathode Preamp/Shaper ASIC** - Three submissions of 16-channel ASIC will be made in 1997.
2. **Finish development of the Switched Capacitor Array ASIC** - Two submissions of 16-channel ASIC will be made in 1997. For this and the previous ASIC, the goal is to deliver preproduction ASIC samples which meet all design specifications.

3. **Delivery of first round 16-channel Anode Preamp/Shaper ASIC** -
4. **Delivery of first round 16-channel Anode Discriminator** - For both the Anode Preamp/Shaper and Discriminator, two additional submissions for 4-channel engineering ASIC and the first submission of 16-channel ASIC will be made. The goal is to deliver first round full size ASICs for chamber tests.
5. **Finish development of the Cathode Readout Controller ASIC** -
6. **Finish development of the Anode Readout Controller ASIC** - For both the Anode and Cathode readout controllers, the FPGA logic will be fully implemented and tested.
7. **Finalize conceptual design of Motherboard DAQ Interface** - The logic for managing the data readout from the front-end boards and data transmission to the DAQ system will be finalized.
8. **Start prototype of Motherboard DAQ Interface** - Preliminary layout of the DAQ Interface Board will be made.
9. **Produce prototype for DAQ part of Cathode 96-channel PC Board** - Prototype of the DAQ part of Cathode Front-end Board with preproduction Preamp, SCA and Controller ASICs together with MUX and ADC will be constructed and tested.
10. **Produce prototype for Anode 96-channel PC Board** - Prototype of the Anode Front-end Board containing first round 16-channel preamp and discriminator ASICs as well as LCT circuitry will be constructed and tested.
11. **Produce Pilot Readout System** - A pilot readout system consisting of 384 cathode channels and 192 anode channels will be constructed for testing of chamber prototype P2.

Beyond 1997, the timetable we are aiming for is to finish the R&D of all components of the front-end electronics in 1998 and to construct and test a full-fledged pilot system including front-end trigger and motherboard in 1999.

3.1.5 Endcap Muon Trigger

The trigger electronics for the endcap CSC muon system finds muon track segments in each chamber and links them together to determine momentum and reduce background rates. The 25ns muon bunch crossing is determined for each muon segment. Because of the limited bending power in the forward region, the muon trigger is designed for very high precision in the bend coordinate. As a consequence of huge background rates from punchthrough, decays in flight, and low-momentum prompt muons, the trigger is designed to take maximum advantage of the highly redundant CSC chamber system.

In previous reports, progress on the basic conceptual design of the endcap CSC trigger was described. For instance, the system is required to achieve a trigger rate of no more than a few kHz, while the physics requires single muon trigger thresholds between 20 and 40 GeV/c with better than 30% momentum resolution, as well as the possibility of setting a threshold as high as 100 GeV/c. The baseline design appears to achieve these goals [9], and we have entered a period of detailed engineering and prototyping.

Accomplishments Since LOI During FY'96, much progress has been made on the design and initial prototyping of critical sections of the CSC muon trigger electronics, as well as formation of a strong collaboration to carry out the design effort. Highlights of this effort are:

- Initial beam tests of the analog-to-digital interface for triggering in the precision strip coordinate. The 'comparator' circuit uses four comparators per strip in order to attain half-strip resolution. The beam tests showed efficiency for correct half-strip identification to be greater than 98% for most of the azimuth, with tails near edges which are useful inputs to Monte Carlo calculations of optimum segment-finding. These tests used discrete components.

- Development of an ASIC design for the strip comparator circuit just described. The circuit has been designed and laid out, and delivery of the first, 8-channel, prototypes will take place in December.

- Creation of detailed designs for strip and wire segment-finding circuitry. The strip design will soon be prototyped using the comparator ASICs delivered in December.

- Modifications to the baseline CSC trigger design to reduce cost and supply additional capability for handling backgrounds and multi-muon events. One proposed modification is to output up to two muon trigger stubs from each chamber. As a result, the electronics which links muon stubs together will be modified to handle the multiple stubs. Another modification is to collect muon stubs together within 30-degree slices at "port cards". This preformats data for track finding, and greatly reduces the numbers of trigger optical data links.

- Continued background studies with particular attention paid to various possible modifications of the cathode strip patterns. These studies have thus far indicated that the all-radial strips can yield acceptable trigger rates even at highest luminosities. However, some particle-particle background correlations are very hard to simulate and require additional study.

During the past year, the CSC trigger group has been strengthened by the addition of one institution (Rice U.) and two engineers. We have also received considerable engineering support from CERN.

Program for FY 97 We will have a very first version of a Strip Card trigger card in Dec. 96 built by UCLA. Two rounds of strip trigger cards will be built and tested during 1997. The first round in '97 should demonstrate reliable operation and muon stub-finding using revised Comparator ASICs. The second round in '97 should integrate the Strip Card trigger function with those of the Motherboard trigger (see below), and include proper clocking and downloading from the Motherboard.

We anticipate 2 rounds of iteration and testing of the wire card trigger during 1997. The first round in '97 should demonstrate reliable bunch identification and muon stub-finding using custom preamp/discriminators. The second round in '97 should integrate the Wire Card trigger function with those of the Motherboard trigger (see below), and include proper clocking and downloading from the Motherboard. During the latter part of '97 we begin the process of converting Strip and Wire trigger designs into digital ASIC designs which will give very large cost savings.

There will be a prototype Motherboard Trigger card which will handle correlation of Strip LCT and Wire LCTs, as well as distribution of clock and downloading signals to front-end Strip and Wire Cards. This prototype will be tested by the end of 1997 on a CSC chamber with connections to at least one Strip Trigger Card and one Wire Trigger Card. Rice University has taken on responsibility for the Motherboard trigger circuitry and will provide this card.

Simulation studies are also to be used to evaluate the design performance and to finalize the requirements for the CSC trigger. We will improve the muon trigger simulation by including detailed circuit designs as well as test beam data, and use the simulation to set certain parameters of the chamber design. For instance, careful staggering of strip positions may improve position resolution.

The hardware and engineering parts of the R&D program include:

1. Finish development of comparator ASIC
2. Develop FPGA version of Strip LCT logic
3. Develop FPGA version of Wire LCT logic and bunch ID
4. Produce prototype Strip LCT board
5. Produce prototype Wire LCT and bunch ID board
6. Test Strip and Wire LCT algorithms using CSC chamber:
   Demonstrate 1/2-strip algorithm (efficiency, position resolution)
   Demonstrate Strip LCT efficiency, spatial and time resolution
   Demonstrate Wire LCT time resolution (bunch ID)
7. Begin ASIC conversion of the Strip LCT logic
8. Design prototype Motherboard Trigger board
9. Test Motherboard Trigger board in conjunction with Strip and Wire LCT boards:
   Demonstrate on-chamber clock distribution

Demonstrate system integration

Demonstrate 'self-triggering' chamber

3.1.6 Resistive Plate Chambers

The RPC system is considered complementary to any trigger function to be provided by the Cathode Strip Chamber system, especially with regard to muon tracking for momentum triggering. In this way a certain amount of redundancy is built into the forward muon trigger system, just as in the barrel muon system, where RPCs are used to provide the timing and momentum tracking in concert with the drift tube system. It is not the intention of the USCMS Muon Group to undertake construction responsibilities for RPCs or other dedicated trigger chambers. However since we have overall management responsibilities, we are making provision for eventual testing of the final design, and for ensuring the integration of the trigger chambers into the muon system.

3.1.7 Alignment

The measurement of the momenta of muons in CMS achieves its highest precision when position information from the central tracker can be combined with information from the muon stations. The role of the alignment task is to provide relative position information for these detector elements with sufficient precision that one can take full advantage of the intrinsic resolution of the detectors themselves. The approach to alignment as described in the Technical Proposal involves internal alignment of the inner tracker, linkage of the inner tracker considered as a rigid body to reference points accessible to the outer detectors, and finally local alignment of the barrel and endcap stations with respect to the linkage points.

CMS Alignment and Position Monitoring in FY 96 In FY'96, we have set up, tested, and reported to CMS (milestone Oct 96) on prototype ATLAS transparent a-Si optical beam position sensors (ALMY). In addition, we have designed, built, tested, and reported to CMS on our proposed alternate window frame CCD crossed beam position sensor (COPS). Again, we have successfully tested two Z coordinate transfer laser devices and linear potentiometers for R transfers. We have completed the conceptual design of the EMPMS (Endcap Muon Position Monitoring System) including Rasnik link transfers through the Barrel system and the Z linking.

CMS Alignment and Position Monitoring R&D in FY 97 In FY'97, we are obligated to complete an integrated (Tracker, Link, Barrel, Endcap) alignment system test at CERN (CMS milestone). We plan to further test ASIC versions of the Atlas sensors. Furthermore, since our CCD prototype looks so promising, we want to proceed with the development of the digital readout version of the device as our possible final sensor of choice. Finally, we are obligated to provide final designs and prototypes for: sensors, mounts, transfers on prototype detectors, link transfer blocks, calibration fixtures, and Rasnik elements.

3.1.8 Muon System Performance Simulations

Progress and Status of R&D in FY 1996 Detector design depends crucially on knowledge of the backgrounds, and a major part of the simulation effort this past year has been devoted to understanding the radiation environment. Work on the CMS software package CMSIM for the muon system has concentrated on a detailed simulation of cathode strip chambers themselves and on reconstruction algorithms leading to track finding and matching.

Radiation Environment and Background Study At a luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ the LHC will produce on average 8 x 10^8 inelastic p-p interactions per second, presenting the detectors with an extremely hostile radiation environment. The charged particles originating from neutrons are especially likely to be a significant contribution to the occupancy of the muon system because of its large detector elements. Studying the performance of the muon system for triggering and muon reconstruction under simulated realistic background conditions is an especially challenging computer simulation problem since neutron capture cross section is proportional to the inverse of the square root of the kinetic energy of the neutron and is highest for thermal neutrons ($E_n < 0.5$ eV) that can still generate γs in the MeV range. The flux of neutrons within the detector is extremely sensitive to the detector geometry and materials, so the detector geometry must be detailed and complete, and cross section values must be available for all detector materials, including shielding, cables and supports. Important progress has been made in this area. [10]

Cathode Strip Chambers Simulations The simulation of the cathode strip chambers [11] begins with free electron generation and transport. The avalanche charge is distributed across strips and the resulting electronic response is simulated to give digitized data. This digitized data is used to reconstruct clusters of strips for a precise coordinate determination. Excellent agreement of the data from P0 with the results of this simulation package has been shown earlier (Fig. 3).

Muon Reconstruction and Matching Muon reconstruction in CMSIM starts with the digitized hit data and clusters described previously. Tracks are then reconstructed via a Kalman filter using a track model with five parameters at each reference surface; momentum, precise and coarse spatial coordinates, and precise and coarse tangent angles. In order to obtain the momentum resolution from the muon plus inner tracker fit we must have good capability matching tracks in the muon system to the inner tracker. The extrapolated muon track parameters are used to compare with those of the inner tracker. The high solenidal field is proved to be particularly effective in aiding the matching. The momentum parameter provides the best match to low p_t tracks while the spatial coordinate gives the best match to the high p_t candidates. We have investigated and documented the ability of CMS to match muons in b-jets [12]. Fig. 5 shows the complementarity of momentum- and spatial-matching methods. The resulting matching efficiency is 99%.

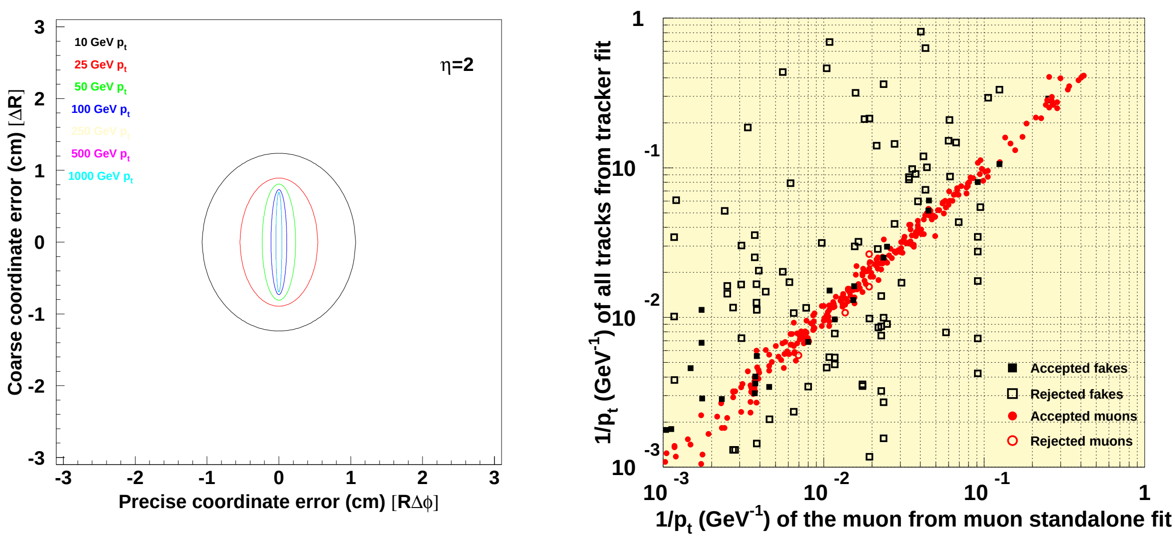


Figure 5: a) Track position errors from reconstructed muons extrapolated to the inner tracker. At large p_t the errors are smaller, therefore matching is better. b) $1/p_t$ of reconstructed muons from b-jets versus $1/p_t$ from the inner tracker fit. At low p_t the momentum match is better.

Program for FY 1997 CMS has formed a Radiation Working Group to coordinate background studies. The feasibility of performing final alignment of the muon system using tracks will have implications on the complexity and cost of the hardware alignment apparatus now being designed. As the chamber design reaches its final form, the trigger assumes first place in the need for detailed simulation. Simulation effort will concentrate on these areas in the coming year.

Radiation Environment and Background Study Expected background rates in the CMS muon system are being examined for various post-Technical Proposal suggestions for changes in the detector and forward shielding design [13]. Yuri Fisyak is now a member of the Radiation Working Group intensively studying the shielding optimization. In addition we are to incorporate the background into the CMSIM simulation. This will enable comprehensive development of triggering and off-line muon reconstruction under realistic conditions, where hits are subject to pileup and multiple hits as registered in detectors.

Software Alignment with Muons A strategy of software alignment is very important since the resolution is only as good as the alignment. For a closed system like CMS it is only natural to use muons to align the muon system. Development of a software alignment plan and its integration into the reconstruction package is under way. We need to find the optimum complementarity between the software and hardware alignment systems. A study of possible systematic errors in the software alignment has been made [14]. Based on those expectations, we will develop a scenario for the software alignment of the CMS muon system including: the use of cosmic muons during detector commissioning runs, strategy for alignment with different luminosities, and a procedure for the relative and absolute calibrations of the magnetic field using, for example, muons from J/ψ.

Muon Trigger Simulations We have simulated the strip and wire signals starting with digitized hit data described in the last section [15]. The pattern finding portion of the CSC trigger is then simulated using the digitized strip and wire data. Local charge tracks (LCT) are formed for both strips and wire groups that can be used to find track candidates for higher level triggers. Simulated strip and wire LCTs in the trigger primitive data banks are available for muon track candidate formation.

A comprehensive and detailed trigger algorithm study is planned. The background LCTs by chamber type has been estimated for the purpose of investigating the potential rate of ambiguous multiple triggers that might challenge a forward muon trigger scheme based solely on radial strips. We have concluded [16] that the radial strip CSC trigger is adequate even if the backgrounds end up being somewhat higher than our expectations. However, a detailed study of the trigger in a realistic environment will be performed as we now have complete trigger simulation tools in hand.

FY 1997 Costs

A summary of FY'97 endcap muon system costs is shown in Table 10.

Table 10: Endcap Muon System FY 1997 Funding Request (K$).

WBS Number	Activity/Task Description	Institution(s)	FY'97 Req. DOE	FY'97 Req. NSF
1	**Endcap Muon Detector**		**1503**	**83**
	CSC Chambers		**659**	**0**
	P0 prototype		**24**	**0**
1.1.1.1	cosmic ray tests	UC Riverside	24	
	P1 prototype		**161**	**0**
1.1.1.1	Cosmic ray test stand	FNAL,Florida,Purdue	96	
1.1.1.1	P1 tests	FNAL,Florida,Purdue	65	
	P2 prototype		**169**	**0**
1.1.1.1	Design and construction	FNAL,Wisc,Florida,SUNY-SB	169	
	Design R&D		**305**	**0**
1.1.1.1	Performance studies	UCLA, Carnegie Mellon	31	
1.1.1.8	Production plan	FNAL, UCLA, Florida	60	
1.1.1.8	Muon factory development	FNAL,UCLA,Purdue,Florida	199	
	Simulations	UC Davis		
1.1.1.1	HV system design	Florida	15	
	Electronics		**520**	**0**
	Cathode readout		**285**	**0**
1.1.2.1	PA/SH ASIC R & D	Ohio State	70	
1.1.2.1	SCA ASIC R & D	UC Davis	74	
1.1.2.1	SCA test board	UC Davis	16	
1.1.2.1	Control ASIC R & D	Ohio State	70	
1.1.2.1	96ch PC-board development	Ohio State	55	
	Anode readout		**75**	**0**
1.1.2.2	PA/SH ASIC R & D	Carnegie Mellon	25	
1.1.2.2	DISC ASIC R & D	Carnegie Mellon	25	
1.1.2.2	96ch PC-board development	UCLA	25	
	Integration		**160**	**0**
1.1.2.3	Motherboard DAQ prototype	Ohio State	80	
1.1.2.1	Pilot system-cathode	Ohio State, UC Davis	60	
1.1.2.2	Pilot system-anode	Carnegie Mellon	20	
	Steel Design		**224**	**0**
	Engineering		**224**	**0**
	Endcap iron design	Wisconsin	200	
1.1.3.1	Endcap integration	Wisconsin	24	
	Trigger		**60**	**0**
1.1.2.4	**Frontend design**	UCLA,Rice	**60**	**0**
	Alignment			**83**
	Integrated System Test		**0**	**83**
1.1.7.2	Sensors, electronics	Northeastern, Fermilab		83
	RPC Chambers		**40**	**0**
1.1.8	**R & D engineering**	Florida	**40**	**0**
	Endcap Management	Florida, Wisconsin	**0**	**0**

3.2 Hadron Calorimetry

3.2.1 Introduction

The basic functions of the CMS calorimeter systems, in conjunction with the tracking system, are to identify and measure the energy of electrons and photons, to measure the energies and directions of particle jets, and to provide hermetic coverage for measuring missing transverse energy [17]. The physics requirements that guide the design of the calorimeter are reviewed in the next section, while the calorimeter system is described in Sections 3.2.2 and 3.2.3. The central pseudorapidity range ($|\eta| < 2.6$) is covered by the barrel and endcap calorimeter system (HB/HE and EB/EE), while the very forward region ($2.6 < |\eta| < 5.0$) is covered by the very forward calorimeter system (HF). The barrel and endcap calorimeters sit inside the 4 Tesla field of the CMS solenoid and hence are necessarily fashioned out of non-magnetic material (copper or brass). The barrel hadron calorimeter inside the solenoid is relatively thin. To ensure adequate sampling depth in the region $0.0 < |\eta| < 1.5$ an outer hadron calorimeter (a hadron shower "tailcatcher") is installed outside the solenoid coil in the central pseudorapidity region. The active element of the central hadron calorimeter readout consists of 4 mm thick plastic scintillator tiles with wavelength-shifting fiber readout. The organization of the CMS HCAL management charged with construction and operation of HCAL is shown in Fig. 6.

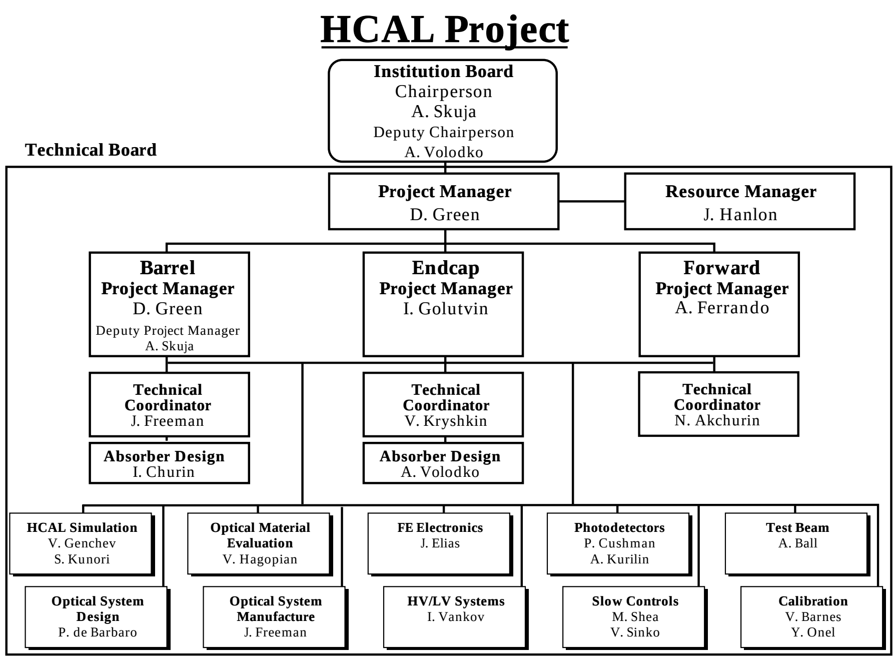


Figure 6: CMS HCAL Project organization.

3.2.2 Hadron Calorimeter Design

Globally, the hadron calorimeter can be considered in two pieces: (a) a central calorimeter ($|\eta| < 2.6$) in which we require excellent jet identification and excellent single particle and jet resolution; and (b) a forward/backward calorimeter ($2.6 < |\eta| < 5.0$) with modest hadron energy resolution but with good jet identification capability. The forward calorimeter is physically separated from the central calorimeter, its front face being located at $\pm$ 11.0 m. from the interaction point.

The Central Hadron Calorimeter

The central calorimeter is divided into a central barrel and two endcap calorimeter sections. The central calorimeter is located inside the CMS 4 Tesla solenoidal field, except for a "tailcatcher" placed outside the coil. The central barrel is divided into two half sections, each half section being inserted from either end of the barrel cryostat surrounding the superconducting solenoid. The detailed design of HCAL has been optimized using data sets taken in test beams for SDC R&D [18]. An illustration of the tower structure of the barrel and endcap regions is shown in Fig. 7.

There are a total of 19 sampling layers in the barrel hadron calorimeter. The barrel hadron calorimeter consists of two depth segments, the first with 9 layers of 30 mm absorber (HAC1), followed by 8 layers of 60 mm absorber (HAC2). Both sides of the innermost muon absorber plate is also instrumented with scintillator to measure hadron shower leakage beyond the cryostat. This design has been arrived at by optimization using data taken in a test beam for CMS in 1995 and 1996. Independent readout of the channels is needed to achieve a resolution without long non-gaussian leakage tails.

The half barrel consists of 18 identical wedges (weighing 22 Tonnes each), constructed out of flat absorber plates parallel to the beam axis. The body of the calorimeter is copper but the inner and outer plates are stainless steel. Each wedge module is assembled from staggered individual copper and outer stainless steel flat plates that are bolted together into a complete unit and its outer surface machined to the required precision after assembly. The bolted design has no projective dead material

The hadron endcap is manufactured out of 18 identical wedges (14 Tonnes/wedge) matching the barrel segmentation. The plates are perpendicular to the beam direction. To improve shower energy resolution each endcap is segmented longitudinally (in depth) into two different sampling hadron compartments (HAC1 and HAC2) of 50 mm and 100 mm copper absorber thickness. There are 9 layers of fine sampling and 12 of coarse sampling.

The effective absorber thickness increases as the polar angle varies as $1/\sin\theta$. The barrel absorber thickness varies from a λ of 5 at $|\eta| = 0$ to a λ of 10.8 at $|\eta| = 1.4$. It follows that the stochastic resolution term in the barrel depends only on the physically relevant variable $E_t = E\sin\theta$. A smooth transition is made to the endcap region at $|\eta| = 1.4$. However, two η segments in this region are traversed by a diagonal 120 mm gap to provide cable and fiber paths to the outer detector. The total absorber thickness in the endcap averages about 11 λ, to allow for the logarithmic increase in depth needed for the containment of higher energy

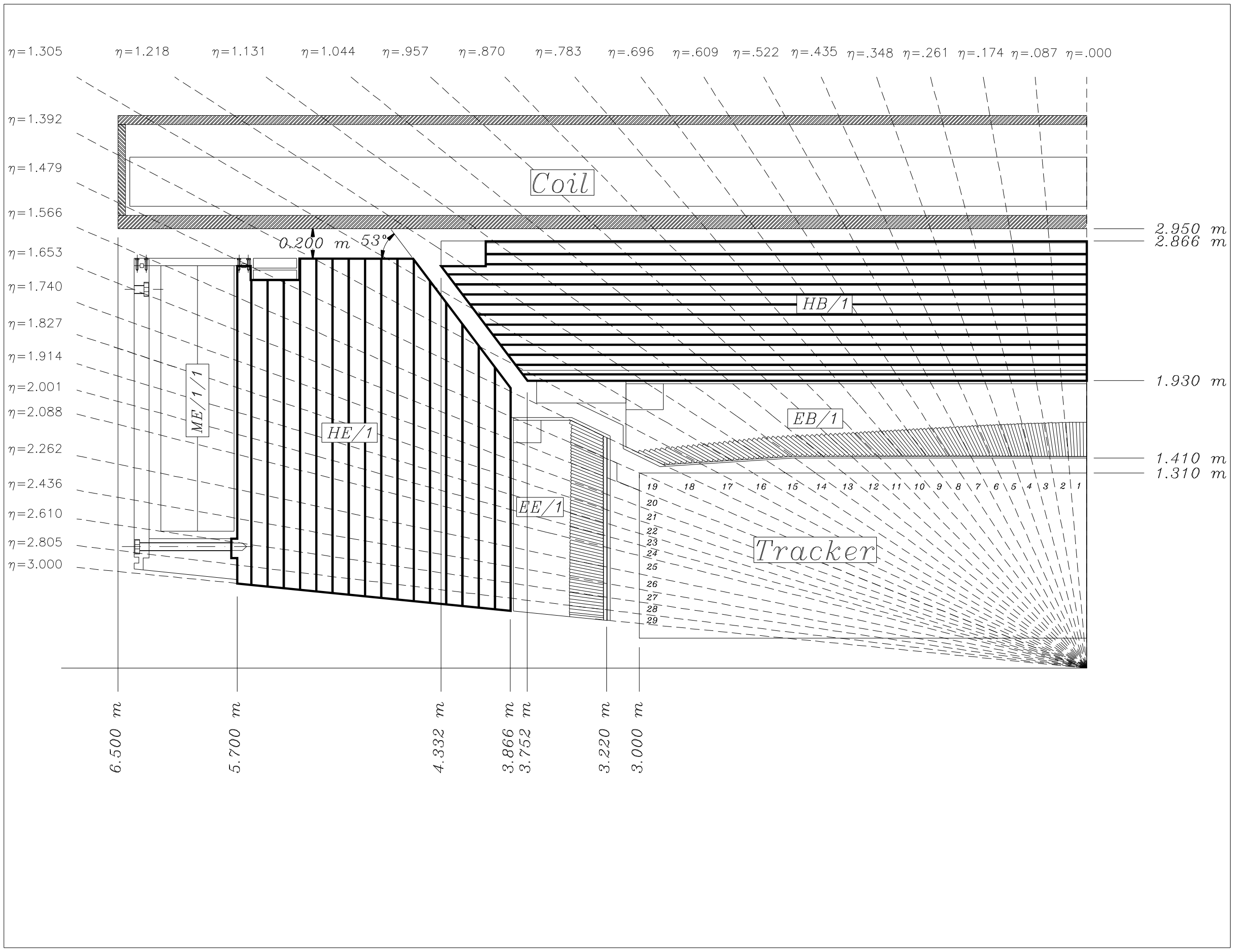


Figure 7: The tower structure of HCAL for the barrel and endcap regions.

showers. The electromagnetic calorimeter adds about 2 λ of absorber in front of the hadron calorimeter.

The active medium throughout the central calorimeter consists of 4 mm thick plastic scintillator tiles with wavelength-shifting fiber readout. The transverse segmentation of the calorimeter is achieved by choosing appropriate size of scintillation tiles, which are arranged in projective towers pointing back toward the interaction region. The nominal hadron calorimeter transverse segmentation is fixed at $\Delta\eta \times \Delta\phi = 0.09 \times 0.09$, which matches the wedge structure of the calorimeter (each wedge consisting of 4ϕ segments).

The CMS muon iron structure is divided into 5 barrel disks and 2 endcap disks. The central barrel disk supports the solenoid and its cryostat vessel. The cryostat vessel in turn supports all the barrel detectors that are mounted inside it, both calorimeters and trackers. The remaining four barrel sections consist of the muon iron and the barrel muon chambers. The two CMS endcap disks support all of the endcap detectors: the calorimeters and the endcap muon system. The very forward calorimeter is mounted independently.

The barrel hadron calorimeter halves hang from rails attached to the inside of the cryostat vessel. This rail system is parallel to the beam axis and divides the cryostat vessel into two equal longitudinal sections, with the upper section of the calorimeter pressing down on the rail, and the lower part hanging down from it. The barrel electromagnetic calorimeter sits on rails mounted on the lower segments of the barrel calorimeter, while the endcap electromagnetic calorimeter is mounted on the front face of its corresponding hadron endcap. The central tracking system, in turn, is mounted on rails attached to lower regions of the barrel electromagnetic calorimeter.

The endcap hadron calorimeter is cantilevered from the endcap flux return iron. It is attached by its stainless steel backplate to a mounting plate fixed to the endcap muon iron (flux return). This mounting fixture may be augmented by an stainless steel pipe of 50 mm thickness running along the inner radius of the endcap system.

The Forward Calorimeter

In December 1995, the technology for the very forward calorimeter (HF) was chosen: the original parallel plate calorimeter was rejected in favor of the US developed quartz fiber calorimeter. The US groups who advocated and demonstrated this technology were from Boston University, Fairfield, Iowa and Texas Tech.

The quartz fiber calorimeter makes full use of advanced US technology, particularly that of highly purified SiO_2, with an OH^- content below 100 ppb, which are the only fibers that have passed the radiation, mechanical and optical specifications. The US introduced the use of sub-500 micron diameter fibers, using 300 micron fibers in the latest prototypes. Additionally, the US team pioneered: low background air and bent fiber readouts for spaghetti calorimetry; all-metal envelope, thin window PMTs for low background calorimeter readout; looped-fiber radiation damage sensing calibration fibers; laser-grooving, photolithographic grooving and electrochemical etching techniques to achieve grooving on the absorber plates for the fibers as fine as 6 grooves/cm of 350 micron grooves, up to 1.8 m long, and novel methods of pulsed light injection for calibration.

The quartz technology and technical team has demonstrated several significant milestones:

- Construction in less than six months of a full hadronic module with nine towers with a weight of 1 Tonne, with a total of two hadronic and three electromagnetic prototypes. This is unlike any other LHC very forward calorimeter to date, and gives enormous confidence in the ability of the group as constituted to carry out this project.

- Demonstration of integrated signals from 375 GeV hadrons in less than 6 ns, sufficient to reject background events from interactions in the final quads by time-of-flight and signal shape. Moreover, pileup is not an issue for this device either.

- Demonstration of energy resolution sufficient to reach the inherent limits from jet fluctuations in the forward region.

-Demonstration of a visible shower transverse width 2.5 times narrower than ionization devices. It will be the only forward calorimeter at LHC where the shower width is smaller than the jet cone at eta of 4.5.

- Demonstration of true projectivity and hermeticity. The signal size and resolution varies by less than 1% across tower boundaries and by less than $1-2\%$ when the angle of incident particles is changed from 0 degrees of tilt to the fiber direction up to 6 degrees tilt. This is again due to the US technology of 300 micron diameter fibers.

These technology milestones are unique and novel based on our SSC/GEM experiences and the latest developments in the associated technologies.

3.2.3 Optical Design

The hadron calorimeter barrel and endcap will consist of a large number of towers ($\sim$3400). In the barrel, each tower will have 18 ot 19 layers of scintillator tiles grouped in depth into 3 samplings, while in the endcaps the 21 layers of scintillator will be instrumented into 2 sampling depths. In order to limit the number of individual elements, the tiles in a given layer constitute a single mechanical unit called a "megatile". The eta-phi segmentation in the Barrel region is $16(\eta) \times 2(\phi)$ or $16(\eta) \times 1(\phi)$. These 16 or 32 tiles in one layer of a wedge are organized into a single mechanical unit. A subset of tiles is cut out of scintillator, the edges painted white, and then attached to a plastic substrate with plastic rivets. The light from each tile is collected by a wave-length shifting (WLS) fiber that is placed in a machined groove in the scintillator. After exiting the scintillator the WLS fiber is spliced to a clear fiber that transports the light to the edge of the megatile. The clear fiber terminates at a multi-fiber optical connector at the megatile boundary. Multi-fiber optical cables carry the light from the megatiles to decoder boxes where the fibers from the different layers comprising a eta-phi depth segment are bundled to an optical transducer. The megatile along with the readout fibers would be packaged in pans, or scintillator trays, which would be inserted into the calorimeter absorber structure. After the installation of the trays, optical fibers are connected between trays and the photodetectors.

3.2.4 R&D work in 1996

We constructed a test calorimeter that was shipped to CERN where it was placed in a large existing superconducting magnet. It had up to 19 planes of scintillator megatiles interleaved between copper absorber plates. The megatiles were attached to optical cables that carried the light to photodetectors. We installed a laser system, an LED system and a moving source system similar to those calibration tools to be used for the final CMS detector. An inert material mockup simulated the cryostat plus coil of CMS.

Using this device we were able to explore: (1) effects of magnetic field on shower development; (2) effects of the magnetic field on our source calibration strategies; (3) strategies for optimizing detector resolution using the planned three independent depth segment measurements; (4) strategies for optimizing detector resolution with the crystal electromagnetic calorimeter in front; (5) develop an understanding of the calorimeter e/π response with the crystal electromagnetic calorimeter in front.

The photon transducer was a challenging feature of our design since it had to operate inside a 4 Tesla field. We have decided on proximity focussed hybrid phototubes (HPD for short) as our baseline and are exploring different manufacturers of this device.

The US group constructed and provided engineering support for the design of a new HF electromagnetic module. This prototype was specifically designed to test longitudinal electromagnetic-hadronic segmentation, the performance of the 180° readout with electrons, and to create long fiber bundles similar to those to be used on the actual experiment and to test possible induced backgrounds from particles traversing the fiber bundle, with an interaction trigger in the test beam.

There were two beam test runs at CERN this year in July and August of 1996. The on-line and preliminary results indicate that the calorimeter is linear with less than 1% error for electrons in the energy range tested (8–250 GeV). The energy resolution for electrons is also dominated by photostatistics and it is $107\%/\sqrt{E}$. Data analysis is continuing.

3.2.5 The CMS HCAL work in 1997

The costs associated with the HCAL program for FY'97 are shown in Table 11.

During 1997 we will incorporate the knowledge gained from the test beam modules as well as from our initial conceptual engineering design to build a fully instrumented full size preproduction barrel wedge. A second such wedge will be built in early 1998. Both wedges will be tested in the H2 test beam in 1998 in the final barrel configuration.

We will have copper and steel plates manufactured at a chosen manufacturing site, which could be the production site as well. These plates will then be shipped to Fermilab where they will be bolted together and the adequacy of the bolting pattern tested. At the completion of construction of a satisfactory mechanical absorber wedge, it will be instrumented with scintillator trays, the calibration system, HPDs and a readout system. All systems will be verified in a cosmic ray exposure at Fermilab before shipment to CERN.

The additional knowledge gained and lessons learned from the manufacture and instrumentation of the preproduction wedge will be incorporated into the final design of the CMS hadron calorimeter barrel (HB) system.

In addition we have to prepare for CERN a Technical Design Report (TDR) with all systems engineered to an adequate level by June 1, 1997. The TDR will cover the entire central hadron calorimeter system (HB/HE).

The HF activities for 1997 include:

1. Concentrate on the light yield of the detector (QQ, QP, NA, double-cladding, redesign matrix, etc.)

2. Study construction techniques that are suitable for the final detector (grooved plates, thick plates with drilled holes, physics or square towers, etc.)

3. Concentrate on the photodetectors and understand the test data and perform mea-

surements in lab (fast rise time and large peak currents, cathode materials, etc.)

4. Start second phase engineering (integration, costing, detailed components).
5. High energy Fermilab beam tests with 800 GeV if available.
6. Consider construction of preproduction prototype (international resources may be complemented with a modest US support).
7. TDR
8. Continue with radiation damage studies.
9. Data analysis of FY'96 test data.
10. Study of new mirroring technology for QP fibers and develop an off-line mirror test protocol.
11. Design of 3×3 air light-guides and dummy fiber-ribbon readout.
12. HV-HV interface test and MC study of HF edge spray.
13. High rate beam test at CERN.

Table 11: Hadron Calorimeter FY 1997 Funding Request (K$).

WBS Number	Activity/Task Description	Institution(s)	FY'97 Req. DOE	NSF
2	**Hadron Calorimeter**		**1650**	**211**
2.1	**Barrel HCAL**		**1430**	**211**
	Optical System Design		**105**	**95**
2.1.1.2	Optical materials evaluation	FSU	15	
2.1.1.2	Optical prototyping	Rochester	15	
2.1.1.2	Optical connectors	UIC		45
2.1.1.5	Fiber splicing machine improvements	Mississippi	30	
2.1.1.5	Moving source scanning table	FSU	35	
2.1.1.5	UV fiber assembly scanner	FNAL,Notre Dame	10	50
	Calibration System		**115**	**0**
2.1.1.3	Laser system development	Iowa, FSU	30	
2.1.1.3	Source mover development	Purdue,FNAL	85	
	Photodetector Tests (HB and HE)		**70**	**0**
2.1.1.3	Evaluate photodetector options	UCLA, Minn, Virginia Tech	70	
	Electronics (HB and HE)		**20**	**0**
2.1.1.4	preamps spice/bench	UCLA, Fermilab	20	
2.1.1.4	EDIA box	Fermilab		
	Preproduction Prototype		**780**	**115**
2.1.1.7	PPP Absorber Plates	Fermilab	365	
2.1.1.7	PPP Absorber Assembly	Fermilab	125	
2.1.1.7	PPP Optical system	FNAL,Roch,UIC	210	20
2.1.1.7	PPP photodetectors	Virginia Tech, FNAL	20	60
2.1.1.7	PPP Calibration system	Iowa, Purdue,FSU,FNAL	20	
2.1.1.7	PPP electronics (HV, LV, preamps)	Fermilab	30	
2.1.1.7	PPP Photodetector Box	Notre Dame,Minn	10	35
	Test Beam Motion Table		**165**	**0**
2.1.1.7	Design/procure	Fermilab, Maryland	165	
	Engineering/TDR		**175**	**1**
2.1.1.1	Engineering design	Fermilab, Maryland	150	
2.1.1.1	Wedge mock-up	FNAL, UMD, Roch, Pur,ND		1
2.1.1.1	Mech. Prototyping	Miss,UMD	25	
2.3	**Forward Calorimeter**		**220**	**0**
	QF Engineering		**25**	**0**
2.3.x.1	Conceptual	Iowa, BU, TT	9	
2.3.x.1	Integration	Iowa, BU	5	
2.3.x.1	Costing	Iowa	3	
2.3.x.1	Detailed Components Study	Iowa	4	
2.3.x.1	Construction Techniques	Iowa, BU	4	
	QF Preproduction Prototype		**20**	**0**
2.3.x.1	Fibers, Pmts,	Iowa, Fairfield, TT	20	
	QF Electronics		**16**	**0**
2.3.x.2	Frontend	BU	5	
2.3.x.1	PMT	Iowa, Fairfield	8	
2.3.4.3	Calibration	Iowa	3	
	QF Test Beam		**39**	**0**
2.3.4	Test Beam	BU,Iowa,Fairfield,TT	39	
	QF TDR		**27**	**0**
2.3.4	TDR	BU,Iowa,Fairfield,TT	27	
	QF Optics		**11**	**0**
2.3.x.1	Light Guides	Iowa, Fairfield	6	
2.3.x.1	QF Mirroring	Iowa, Fairfield	5	
	QF Radiation Damage		**5**	**0**
2.3.4	Radiation Damage Studies	Iowa	5	
	Test Beam Prototypes		**77**	**0**
2.3.4	Prototypes	Iowa	77	

3.3 Trigger and Data Acquisition

3.3.1 Introduction

The 1997 CMS trigger R&D program includes three major activities. The first is the study of the implementation of the trigger algorithms determined from the Requirements Review in November, 1996. The second is the design of the trigger system starting from the results of the preliminary design review in November, 1996 with the milestone of having a intermediate design review in November, 1997. The third is the engineering evaluation and prototyping of hardware proposed for use in the design for the purpose of evaluating the design capability, feasibility, and cost. The goal of the hardware evaluation is to provide the information required for the trigger system design and specifications of interfaces to the Front End, Trigger and DAQ systems.

The FY 1997 CMS Luminosity Monitor R&D program will involve tests of prototype counters and simulation studies of monitoring in the forward region.

The FY 1997 CMS DAQ R&D program consists of four activities. The first is the continuation of the work on the ATM-based Event Builder testbench at FNAL. The second is the completion of the first RDPM prototypes that are capable of reading data through VME64 and writing data through the PCI bus. The third is the completion of simulation studies of event builder architectures. The fourth is the completion of calorimeter-based level 2 trigger algorithms and a first evaluation of tracking-based algorithms.

The US CMS group has a number of leadership roles in the CMS Trigger and Data Acquisition Project (TRIDAS), as shown in Fig. 8. P. Sphicas (*MIT*) is the Chair of the TRIDAS Institutional Board. W. Smith (*Wisconsin*) is the CMS Trigger Project Manager. J. Hauser (*UCLA*) is responsible for the endcap muon trigger. P. Sphicas also is responsible for higher level triggers. I. Gaines (*FNAL*) is responsible for the event builder. J. Branson (*UCSD*) is responsible for Trigger Simulation. Finally, G. Snow (*Nebraska*) is responsible for Luminosity and Beam Background measurements.

3.3.2 Level 1 Calorimeter Trigger

Progress and status of R&D in FY 1996

US CMS is responsible for the regional processing system of the calorimeter level 1 trigger. This system processes the electromagnetic and hadronic trigger tower sums from the calorimeter front end electronics and delivers regional information on electrons, photons, jets, and partial energy sums to the global calorimeter level 1 trigger system. The system begins after the data from the front end electronics is received on optical fibers and translated to signals on copper and ends with cables that transmit the results to the calorimeter global level 1 trigger system. A list of important achievements of this work include:

- Conceptual design of the CMS Level 1 Calorimeter Trigger baseline used in the technical proposal[19].

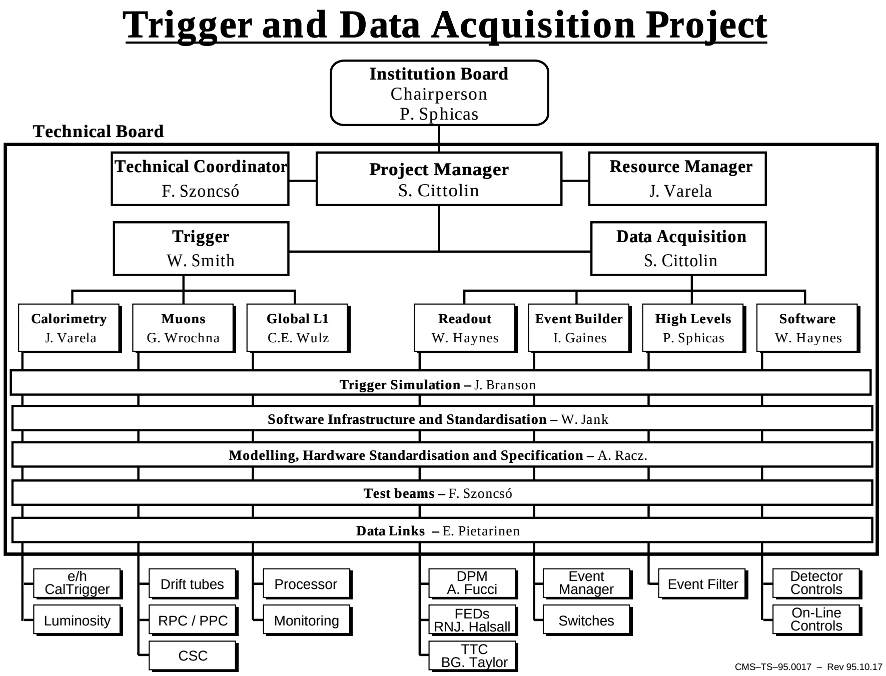


Figure 8: CMS Trigger/DAQ Project organization.

- Design of block diagrams of ASIC's in the conceptual design.
- Development of initial cost and schedule estimates.
- Simulation studies[20, 21, 22, 23] with a parameterized Monte Carlo that demonstrate that the performance of the Calorimeter Trigger design meets the physics requirements of CMS[24].
- A 160 MHz GaAs Adder ASIC designed at U. Wisconsin and built by Vitesse that adds 8 13-bit numbers in less than 25 nsec. This device was tested by Vitesse to work at speeds over 200 MHz, exceeding the design requirement of 160 MHz.
- Evaluation and design of JTAG/Boundary Scan implementation on the ASIC level to develop diagnostic methodology for the conceptual design.
- Design of a Backplane - Data Transmitter/Receiver Prototype system and Adder ASIC tester to verify the viability of the data processing/transmission scheme used in conceptual trigger design. This test, along with the construction of the Adder ASIC, is crucial to demonstrating that the basic technology of boards, backplanes and ASIC's running at 160 MHz is a viable concept for the CMS calorimeter trigger.
- Construction of a 160 MHz point-to-point Backplane Prototype to test the viability of data transfer scheme used in conceptual trigger design.
- Layout of a prototype clock/control board for operation of the backplane.

Program for FY 1997

The task in 1997 is to continue the design of the level 1 calorimeter trigger and to continue the hardware evaluation required to support this design work. Simulation studies are also to be used to evaluate the design performance and to evaluate whether the design meets the requirements for the trigger. Prototype design and construction will prepare for the milestone of a Review of prototype designs of the regional calorimeter logic scheduled for November, 1997.

A major part of the calorimeter trigger system design is the high speed backplane that operates with a large number of point to point connections at 160 MHz. There will be a number of backplane design studies of high volume signal transmission, high density connectors, clock distribution, power distribution, cooling, location of cabling and accessibility for debugging and maintenance. These studies will use the prototype backplane to perform extensive tests to determine its operational characteristics and feasibility for use in the final system. We intend to construct prototype Receiver Boards and Electron Isolation Boards and perform a test of data transmission from the Receivers Boards through the backplane and onto the Electron Isolation Boards. We will develop the software necessary to operate these prototype boards and read them out with thorough diagnostics.

We will continue the work on the Calorimeter trigger ASICs that form the heart of the system. We will test the prototype GaAs technology Adder ASIC's. We will continue design work on the Isolation, Sort, and Synchronization ASICs. We intend to carry these designs far enough to have preliminary schematics, which will tell us whether these devices can be built and function as proposed.

We will continue our board and circuit design work to develop energy summation and electron identification techniques to refine the technology for electron/photon and jet triggers. We will continue physics simulation studies to guide these investigations. We will also develop design requirements in order to set up data-flow diagrams and VHDL descriptions. We will develop models for and study the overall calorimeter trigger latency. Finally we will address the issue of diagnostics in order to develop a global philosophy that can be applied across trigger systems, involving both ASICs and boards. We will continue the investigation begun with the Adder ASIC with a study of the J-Tag/Boundary Scan scheme on the board level. We will develop the software to operate and test the Boundary Scan diagnostics.

We will also continue to study the overall CMS level 1 trigger latency. We also plan to investigate trigger system engineering. Specifically this involves power and cooling, cable requirements, physical size of electronics, location of electronics and access requirements.

In summary, the hardware and engineering parts of this R&D program include:

1. Trigger System Design: refine the specification of the numbers of ASICs, boards, cards and crates, and what is on each. Define the interfaces for each board and the I/O.

2. Electron Isolation ASIC preliminary design: produce schematics based on Vitesse libraries.

3. Sort ASIC preliminary design: produce schematics based on Vitesse libraries.

4. Backplane Prototype construction/studies: test high volume signal transmission, connectors, clock distribution, power distribution, and cooling.
5. Electron Isolation Prototype Board for testing of data transmission path from backplane.
6. Dataflow test from prototype receiver card to prototype backplane to prototype electron isolation card.
7. Jet/Summary Card preliminary design.
8. Study of intercrate data transfer techniques.
9. Preliminary design and test of board level JTAG/Boundary Scan diagnostics.
10. Refine the calorimeter trigger latency calculation.
11. Produce a more detailed cost and schedule.

The cost for the FY 1997 US CMS calorimeter trigger R&D program is shown in table 12.

3.3.3 CSC Muon Trigger

Progress and status of R&D in FY 1996

The trigger electronics for the endcap CSC muon system finds muon track segments in each chamber and links them together to determine momentum and reduce background rates. The 25ns muon bunch crossing is determined for each muon segment. Because of the limited bending power in the forward region, the muon trigger is designed for very high precision in the bend coordinate. Because of huge background rates from punchthrough, decays in flight, and low-momentum prompt muons, the trigger is designed to take maximum advantage of the highly redundant CSC chamber system.

In the 1995 US CMS LOI[1], progress on the basic conceptual design of the endcap CSC trigger was described. For instance, the system is required to achieve a trigger rate of no more than a few kHz, while the physics requires single muon trigger thresholds between 20 and 40 GeV/c with better than 30% momentum resolution, as well as the possibility of setting a threshold as high as 100 GeV/c. The baseline design appears to achieve these goals, and we have entered a period of detailed engineering and prototyping.

During FY'96, much progress has been made on the design and initial prototyping of critical sections of the CSC muon trigger electronics, as well as formation of a strong collaboration to carry out the design effort. Highlights of this effort are:

- Initial beam tests of the analog-to-digital interface for triggering in the precision strip coordinate. The 'comparator' circuit uses four comparators per strip in order to attain half-strip resolution. The beam tests showed efficiency for correct half-strip identification to be greater than 98% for most of the azimuth, with tails near edges which are useful inputs to Monte Carlo calculations of optimum segment-finding. These tests used discrete components.

- Development of an ASIC design for the strip comparator circuit just described. The circuit has been designed and laid out, and delivery of the first, 8-channel, prototypes will take place in December.

- Creation of detailed designs for strip and wire segment-finding circuitry. The strip design will soon be prototyped using the comparator ASIC's delivered in December.

- Modifications to the baseline CSC trigger design to reduce cost and supply additional capability for handling backgrounds and multi-muon events. One proposed modification is to output up to two muon trigger stubs from each chamber. As a result, the electronics which links muon stubs together will be modified to handle the multiple stubs. Another modification is to collect muon stubs together within 30-degree slices at "port cards". This preformats data for track finding, and greatly reduces the numbers of trigger optical data links.

- Continued background studies with particular attention paid to various possible modifications of the cathode strip patterns. These studies have thus far indicated that the all-radial strips can yield acceptable trigger rates even at highest luminosities. However, some particle-particle background correlations are very hard to simulate and require additional study.

During the past year, the CSC trigger group has been strengthened by the addition of one institution (Rice U.) and two engineers. We have also received considerable engineering support from CERN.

Program for FY 1997

We will have a very first version of a Strip Card trigger card in Dec. 96 built by UCLA. Two rounds of strip trigger cards will be built and tested during 1997. The first round in '97 should demonstrate reliable operation and muon stub-finding using revised Comparator ASICs. The second round in '97 should integrate the Strip Card trigger function with those of the Motherboard trigger (see below), and include proper clocking and downloading from the Motherboard.

We anticipate 2 rounds of iteration and testing of the wire card trigger during 1997. The first round in '97 should demonstrate reliable bunch identification and muon stub-finding using custom preamp/discriminators. The second round in '97 should integrate the Wire Card trigger function with those of the Motherboard trigger (see below), and include proper clocking and downloading from the Motherboard.

The present segment-finding designs use FPGA technology which is both expensive and power-hungry. The logic elements of the Strip and Wire LCT FPGAs are fairly standard digital circuits which can be converted to ASIC designs, resulting in about an order of magnitude reduction in chip costs. This is necessary, given the very large numbers of chips.

During the latter part of '97 we begin the process of converting Strip and Wire trigger designs into digital ASIC designs which will give very large cost savings.

There will be a prototype Motherboard Trigger card which will handle correlation of Strip LCT and Wire LCTs, as well as distribution of clock and downloading signals to front-end Strip and Wire Cards. This prototype will be tested by the end of 1997 on a CSC chamber with connections to at least one Strip Trigger Card and one Wire Trigger Card. Rice University has taken on responsibility for the Motherboard trigger circuitry and will provide this card.

Simulation studies are also to be used to evaluate the design performance and to finalize the requirements for the CSC trigger. We will improve the muon trigger simulation by including detailed circuit designs as well as test beam data, and use the simulation to set certain parameters of the chamber design. For instance, careful staggering of strip positions may improve position resolution.

The hardware and engineering parts of the R&D program include:

1. Finish development of comparator ASIC
2. Develop FPGA version of Strip LCT logic
3. Develop FPGA version of Wire LCT logic and bunch i.d.
4. Produce prototype Strip LCT board
5. Produce prototype Wire LCT and bunch i.d. board
6. Test Strip and Wire LCT algorithms using CSC chamber:
   Demonstrate 1/2-strip algorithm (efficiency, position resolution)
   Demonstrate Strip LCT efficiency, spatial and time resolution
   Demonstrate Wire LCT time resolution (bunch i.d.)
7. Begin ASIC conversion of the Strip LCT logic
8. Design prototype Motherboard Trigger board
9. Test Motherboard Trigger board in conjunction with Strip and Wire LCT boards
   Demonstrate on-chamber clock distribution
   Demonstrate system integration
   Demonstrate 'self-triggering' chamber

The cost for the FY 1997 US CMS muon trigger R&D program is shown in table 12.

3.3.4 Luminosity Monitor

Program for FY 1997

The R&D effort in FY'97 will focus on simulation studies for elastic and inelastic rate monitoring in the forward region and prototype studies of scintillator-based and quartz-based detectors for the dedicated luminosity and background monitors. The scope and objectives of the Luminosity Monitoring project are described in the R&D request submitted to the NSF[2].

We will machine, assemble and test prototype counters for the CMS luminosity monitor and construct a cosmic ray stand for testing the prototypes. Prototypes will be made from polystyrene and quartz scintillator stock, wavelength-shifting optical fibers and wrapping materials. We will study the light collection and uniformity characteristics of prototype counters for the CMS luminosity monitor. We will procure four phototube assemblies (photomultiplier tube, base, magnetic shield) and data acquisition electronics, including a CAMAC-based analog-to-digital converter and interface electronics, for these tests. We will perform simulation studies of the particle multiplicity, rates and radiation exposure which will be encountered by the luminosity and beam background monitors. In addition, we will investigate the use of event rates of various inclusive particle production processes to supplement the information from the dedicated luminosity monitor.

The activities above will culminate in an integrated proposal for the luminosity and beam background monitoring techniques which will be presented to the CMS collaboration for review in the summer and autumn of 1997. The cost for the FY 1997 US CMS luminosity monitor R&D program is shown in table 12.

3.3.5 Data Acquisition (DAQ)

Status in FY 1996 & Program for FY 1997

The FY 1997 CMS Data Acquisition R&D program is a natural continuation of our current R&D in FY 1996 and consists of four major activities:

- The extension of the prototype test-bench for event-building schemes. This prototype was procured in FY 1996.
- The development, in collaboration with CERN-CMS, of prototypes of two different architectures for the Readout Dual Port Memories (RDPM), the basic unit of the CMS DAQ system.
- Simulation studies of switching architectures and protocols, and comparison with results from the Event Builder testbench.
- The development and study of processor based level 2 trigger algorithms to further validate the latencies and rejection factors assumed in the design of the DAQ.

Event Builder Testbench

In FY 1996 we installed a FORE ATM switch at Fermilab. A set of eight CPUs (four Motorola MVME-1603 and four Radstone RS603) act as event data sources and destinations, respectively. A ninth processor acts as a manager responsible for the synchronization of inputs and outputs. At this stage, the only PCI-ATM interfaces available are the ones for a link speed of 155 Mbit/sec. We have procured eight such interfaces and also ported the CDF Data Acquisition System (with the exception of the Front-End Readout) into the testbench. An I/O driver for the PMC-ATM card was designed, written and installed. This mini-DAQ (a 4×4 system) was made functional in May 1996. Following this, we performed several measurements on this prototype.

In FY 1996 we tested two event-building architectures: the barrel-shifter one and a second one in which no source synchronization is established, but overflows at the destination are avoided by limiting the speed of each source. Preliminary results indicate that the second method results in a higher data throughput for this small DAQ system.

The Event Builder Testbench program of work consists of three stages:

1. Comparison of synchronous vs asynchronous switch operation
2. High speed ATM (620 Mbit/sec) switch tests
3. Implementation of two options of control transmission information (via the reverse switch datapath and via an independent, external, control path), along with measurement of the timing overheads associated with each option.

RDPM Development

In FY 1996 we proceeded with the first development of two versions of the Readout Dual Port Memory (RDPM) modules, the basic unit of the CMS DAQ system. One version of the RDPM is designed using FPGAs. The second version contains an embedded processor, the Texas Instrument C80 chip.

The FPGA version, designed by CERN-MIT and built at CERN, has been made to work in FY 1996. The memory management unit has been completely debugged. We are currently testing the long-term high-rate reliability of the transfers through the RDPM, both at MIT and at CERN.

The embedded processor version, design and built by the UCSD group, has also progressed to the level of a first prototype in FY 1996. The VME64 and PCI interfaces have been debugged, and first performance measurements result in a throughput of 89 MBytes/sec – for a simulated event size of 1kByte. The throughput is higher for larger event sizes.

The RDPM program of work for FY 1997 consists of the following tasks:

1. Test prototype 2 of FPGA RDPM (VME64 and PCXI interfaces)
2. Use FPGA RDPM prototype in Event Builder testbench

3. Complete debugging and testing of the embedded-processor prototype RDPM
4. Use embedded-processor RDPM to drive a single ATM channel
5. If time allows, use one embedded-processor RDPM in the Event Builder testbench.

On the event-builder simulation front, in FY 1996 we completed the C++ software package that was created in FY 1995. This included the addition of the processor farm and event management protocol (distributed) in the simulation package. We are currently extending the simulation to allow for two different architectures, with and without a central Event manager intelligence. This is also the plan for FY 1997, namely to complete the simulation of these two architectures, and eventually compare to the results obtained from the extended Event Builder Testbench.

Finally, on the level 2 algorithms, in FY 1996, the software structure that will serve as the basic development environment for High Level Trigger software has been created. We are currently studying calorimeter-based algorithms. In FY 1997 we will study the possibility of including information from the tracking detectors in the level 2 algorithms.

3.3.6 Total FY 1997 Program

The costs for the FY 1997 Trigger/DAQ R&D program are listed in table 12.

Table 12: Trigger/DAQ FY 1997 Funding Request (K$).

WBS Number	Activity/Task Description	Institution(s)	FY'97 Req. DOE	FY'97 Req. NSF
3	**Trigger and Data Acquisition**		**550**	**109**
3.2	**L1 Calorimeter Trigger**		**250**	**0**
	Equipment (Backplane)		**16**	**0**
3.2.7	Crate	Wisconsin	2	
3.2.6	Backplane construction	Wisconsin	10	
3.2.14	VME controller	Wisconsin	4	
	Equipment (jet & elec trig)		**98**	**0**
3.2.2	Electron Iso. Card Proto.	Wisconsin	8	
3.2.1	Receiver Card Rev. B	Wisconsin	10	
3.2.10	ASIC Development.	Wisconsin	80	
	Engineering and Technical		**136**	**0**
3.2.12	1 MY engineering	Wisconsin	100	
3.2.13	0.5 MY Technician	Wisconsin	36	
3.1	**L1 Muon Trigger**		**160**	**0**
	Equipment		**40**	**0**
3.1.1	LCT, ASIC Conversion	UCLA	10	
3.1.1	Strip/WIre Test Eq.	UCLA	30	
	Trigger Motherboard FPGA's			
	Engineering and Technical		**120**	**0**
3.1.12	1.0 MY engineering	UCLA	80	
3.1.13	0.3 MY engineering	Rice	40	
3.3	**Luminosity Monitor**		**0**	**59**
	Equipment		**0**	**21**
3.3.1.7	PMT assemblies	UNL		2
3.3.1.7	DAQ electronics	UNL		5
3.3.1.7	Disc. and coinc. units	UNL		3
3.3.1.7	Prototype materials	UNL		5
	DAQ and Lumi Monitor	UCLA		6
	Engineering and Technical		**0**	**38**
3.3.1.7	0.3 MY engineering	UNL		20
3.3.1.7	1.0 MY technician	UNL		18
3.4	**Data Acquisition**		**140**	**50**
	Equipment		**86**	**0**
	622 Mbps ATM/SONET adapter (2)	FNAL, Iowa St, MIT, Miss	40	
	155 Mbps ATM/SONET upgrade (8)	FNAL, Iowa St, MIT, Miss	22	
	FPGA RDPM prototypes (1)	FNAL, Iowa St, MIT, Miss	10	
	Waveform Generator	MIT	3	
	RDPM prototypes (4)	UC San Diego	8	
	RDPM (Vortex) board layout	UC San Diego	3	
	Software		**0**	**16**
	C80 development system	UC San Diego		8
	Cadence License	UC San Diego		8
	Engineering and Technical		**54**	**34**
	0.5 MY engineering (Vortex)	UC San Diego	37	
	0.5 MY technician (RDL)	UC San Diego		34
	0.4 MY technician	MIT	17	

3.4 Electromagnetic Calorimetry

3.4.1 Introduction

The CMS ECAL Project organization chart is shown in Fig. 9.

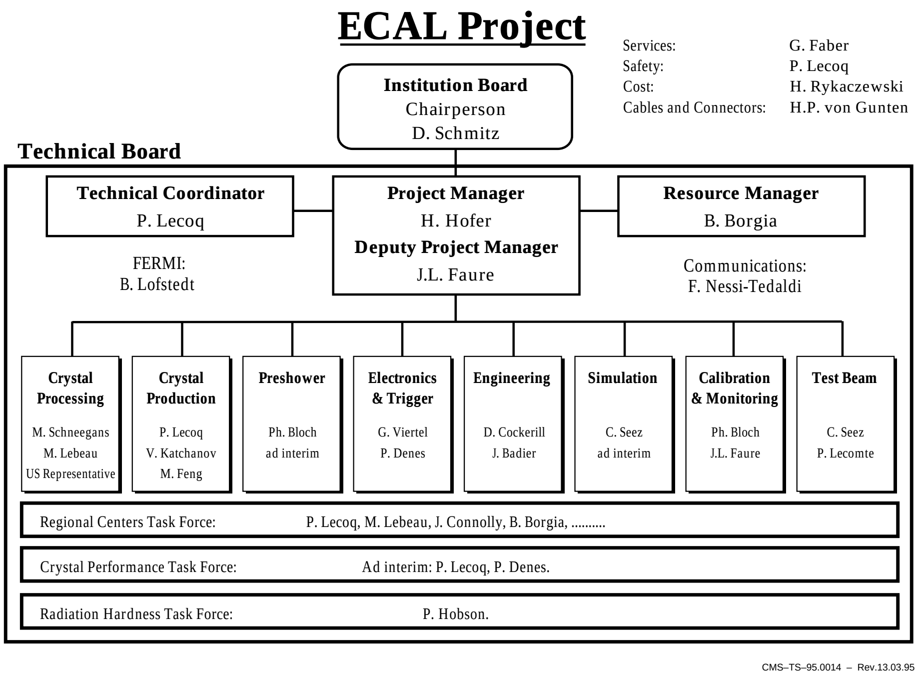


Figure 9: CMS Trigger/DAQ Project organization.

The CMS detector, designed to exploit the full range of physics at the LHC up to highest luminosities, is particularly well poised for SM Higgs discovery via the H $\rightarrow \gamma\gamma$ channel, as well as the supersymmetric Higgs (one of which should have a mass close to the Z, and thus be accessible via the gamma gamma channel). This imposes numerous technical challenges to the ECAL system, in particular for the crystals and the readout

The CMS Electromagnetic Calorimeter will consist of 109,008 crystals of Lead Tungstate ($PbWO_4$) arranged in a barrel (92,880 crystals) and 2 endcaps (8,064 crystals each). The crystals will be 25 radiation lengths long, and cut in tapered shapes to make a hermetic calorimeter. The scintillation light from the crystals is captured by a photodetector, amplified and digitized. The properties of $PbWO_4$ which is a new crystal still very much under development, are summarized in Table 13.

The 4 Tesla magnetic field in CMS, along with the limited light output of $PbWO_4$ places severe constraints on the choice of photodetector. In the barrel region of the detector (crystals perpendicular to the solenoidal field) silicon avalanche photodiodes (APD's) are envisaged. In the endcaps where crystals are parallel to the magnetic field vacuum photodetectors (triode or tetrode) are foreseen.

The US CMS group has a number of leadership roles in the Electromagnetic Calorimeter project, as can be seen in Figure 9: P. Denes (*Princeton* is co-responsible for the electronics; R. Rusack (*Minnesota*) is co-responsible for the photodetectors, and R. Zhu (*Caltech*) is co-responsible for the crystal processing.

3.4.2 Milestones, Schedule and Funding Profile

In order to achieve the high precision which we expect to achieve with the $PbWO_4$ calorimeter, we have to calibrate each crystal equipped with its electronics chain, through to the digitizer, in a test beam. Thus, as soon as crystals are produced they are assembled into 6 $\times$ 6 groups and equipped with the photodetector, electronic readout, monitoring fibers and cooling system. These modules will then be assembled into supermodules for calibration. In order to complete the ECAL installation by 2004, the APD and front-end electronics must be in production at the same time as the crystal production and the monitoring light source must be available for the supermodule beam calibration in 2000. The major milestones that we have to meet in order to complete the installation of the calorimeter on time, are given in Table 14.

The US responsibilities, which are the engineering, electronics, photodetectors and monitoring system, all have to be in production, or complete by the year 2000. Consequently most of the funding for the US part of the ECAL project should be in the years 1998 and 1999.

A summary of the funds required for the FY'97 program is shown in Table 15.

3.4.3 The role of the US groups

The institutions that will participate in the US effort on the CMS electromagnetic calorimeter are: BNL, Caltech, Fermilab, LLNL, Minnesota, Northeastern and Princeton. The items for which we have responsibility in the construction of the calorimeter are the avalanche photodiodes (Minnesota, Fermilab and Northeastern), the front-end electronic readout (Princeton), thermal and other advanced engineering (LLNL), and the monitoring light source (Caltech). Our R&D efforts in the past year and in 1997 are focussed on these

Table 13: Properties of Lead Tungstate crystals

Density	8.2	g/cm^3
Radiation Length	0.92	cm
Decay Time	10	ns
Emission Peak	460	nm
Temperature Coefficient	-2	%/ C
Light Output	$\sim$ 2	p.e./MeV (5 mm APD)

Table 14: Milestones

Item	Completion	Status
Reduce k-factor for EG&G APD	End 1996	Done
Select APD for production	End 1997	
Final barrel mechanical design	Mid 1997	
Final front-end electronics design	Mid 1997	
Setup regional centers for crystal assembly	1998	
Final endcap mechanical design	Mid 1998	
Begin APD production	1998	
Begin crystal production	1999	
Begin supermodule calibration	2000	
Install calorimeter	2004	

areas of responsibility, with additional contributions being made to understand and optimize the $PbWO_4$ crystals by Caltech and BNL.

3.4.4 Progress in 1996 and Plans for 1997

In FY'96 the level of funding for ECAL was $290k. This was divided between our sub-projects: Electronics $100k; Photodetectors $95k; Engineering $50k, and Monitor/Crystal R&D $45k. These funds have been used primarily to develop and test a full-dynamic-range low-noise 40 MHz linear analog-to-digital converter suitable for the crystal calorimeter; to quantify and improve the APD's; to develop a thermal finite element analysis of the complex interface region at the back of the calorimeter and to study the $PbWO_4$ crystal properties. Details of these individual programs follows.

Avalanche Photodiodes This year much of our effort has been devoted to understanding the radiation damage of the APD. One effect suggested both theoretically and by one experimental result was the possibility that the high internal electric field of the APD could increase the dark current of the APD above that which would be expected by radiation damage in ordinary diodes. Measurements which we made at PSI and at ORNL have shown that this enhancement to the radiation damage does not occur at the fields ($\sim 3.10^5$ V/cm) found inside the APD's. Had it been present it would have seriously degraded the signal-to-noise of the calorimeter.

Radiation Damage Measurements Two types of irradiation damage studies were carried out: at ORNL we used the Cf^{252} neutron sources to study slow irradiation of the EG&G and RMD APD's, and at PSI we carried out irradiation studies of Hamamatsu APD's

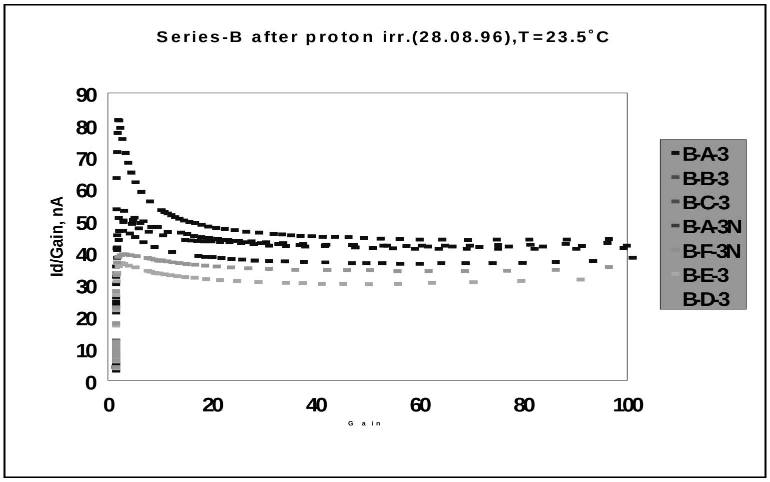


Figure 10: Dark current in the APD divided by the gain plotted as a function of gain for recent Hamamatsu APDs.

with 72 MeV proton. (At 72 MeV the damage done by a proton is about double that of a 1 MeV neutron.)

At ORNL eight different APDs were exposed to neutron fluences ranging up to 10^{13} neutrons/cm^2[25]. The effect of these exposures was to increase the dark current at a gain of 50 to 5 - 10 μA. For the RMD 64 mm^2 (SH8S type) devices, the total dark current at a gain of 50, increased by a factor of 40 to 7μA.

At PSI eight test Hamamatsu APD's were all given doses of 2.7×10^{12} protons/cm^2, corresponding to doses of 5×10^{12} neutrons/cm^2. The dark current increased for these devices to about 4 μA. However, the ratio of the dark current to the gain is a constant once the gain is above 10, see Fig 10. This indicates that the source of the current is mostly from in front of the avalanche region and that there is no field enhancement effect.

The conclusions which can be drawn from these and other related measurements are that:

- There is no field enhancement effect and the damage is consistent with a damage constant of $8.10^{-19} A/cm^3$;
- The dark current decreases by a factor of 8 when the temperature is reduced from 27°C to 1°C, corresponding to an energy level equal to 0.56 eV, half the silicon bandgap;

- If the surface coating of the APD is silicon nitride, there is no degradation to the detector quantum efficiency, whereas if it is silicon dioxide reduction in QE at the shorter wavelengths (< 500nm) is observed.

- The dark current reduces by about 30% over a period of 40 days.

These results have consequences on the calorimeter design. With the current light output level from the crystals, the dark current after irradiation would have to be less than 500 nA to meet our resolution requirement. To achieve the required resolution we can either improve the crystal light output, or increase the surface area of the APD, or cool the APD.

APD development One of the tasks which we have carried out this year, which is still in process, is the improvement of the package of the EG&G APD. The current low-profile ceramic design has been a cause of failures of the APD's. In order to avoid these problems EG&G, under subcontract to the University of Minnesota, are redesigning their package to simplify fabrication and reduce the stresses on the wafer during assembly. Results from this development can be expected by the end of this year.

Plans for 1997 and 1998 The choice of the APD to be used in the crystal matrix will be made in 1998. The collaboration's strategy is to develop two types of APD's so that the cost of the final APD will be decided by competitive bidding. Our collaborators at PSI are working closely with Hamamatsu to optimize their APD, whereas, we in the US are following the development of the EG&G APD.

In the coming year we will continue our work with EG&G. The next step will be to move from 2 inch to 4 inch wafers and to pixellate the APD. Pixellation will allow for an increase in the light collection area while keeping the cost constant. This can be achieved by using only part of the active area so devices with local defects can be used. Thus EG&G can manufacture a 1 cm^2 device, divided into 16 square pixels, with a similar yield to perfect 25 mm^2 APD's, if we use only 12 of the pixels. This will increase the signal by a factor of three and the signal-to-noise, after irradiation, by a factor of 1.7.

In addition to the APD's from Hamamatsu and EG&G we expect to receive from RMD, who, with SBIR sponsorship, are developing a new version of their large area APD optimized for CMS.

We also plan to setup at ORNL a long-term neutron irradiation facility. This will provide the collaboration with a unique facility, where not only APD's but all other sensitive components can be characterized.

Electronics The electronics chain for the readout of the calorimeter will be placed directly behind the calorimeter. The dynamic range it will have to cover is < 50 MeV to > 2 TeV with a sampling frequency of 40 MHz. For each crystal there will be a preamplifier with two outputs for high and low-level signals. These two outputs will be connected to a range selecting sample-and-hold (FPU). The output of this will be connected to a 40 MHz 12-bit flash ADC.

In 1996, the ECAL electronics group constructed a matrix of 3 × 3 $PbWO_4$ crystals with a complete, full dynamic range readout directly behind the crystal. The readout chain consisted of a 120 pF Hamamatsu APD coupled to a two-output full dynamic range preamplifier from the Lyon group. The preamp outputs were connected to the FPU, designed and built by Princeton, which in turn was connected to an ADC. Digital readout for the test was accomplished with logic cell arrays (LCA) and fiber optics constructed for the test by Princeton. The preamp was built in 0.8 μ BiCMOS technology. For the FPU's two different technologies were employed: 0.8 μ BiCMOS and 0.7 μ CHFET (Complementary Heterostructure GaAs [26]). The ADC used was the Analog Devices bipolar 40 MHz voltage-sampling ADC (AD9042). The readout chain, the tests made and the results obtained are described in more detail in reference [27].

The two preamplifier outputs '× 1' and '× 8', are each followed by two amplifiers of gain 1 and 4. These amplifiers (which were external, commercial op-amps for the tests) create four outputs corresponding to gains 1, 4, 8 and 32 each with a programmable pedestal offset. These four outputs serve as the analog inputs to the FPU.

The FPU chip consists of four sample-and-holds, comparators, digital logic, multiplexers and a final buffer to drive the signal off chip. It operates in the following way: Every 25 ns, the four amplified inputs are stored by the sample-and-holds. Digital logic is used to select the highest gain signal which is below the threshold and the selected channel is multiplexed out. After the ADC conversion begins, the sample/holds return to sample mode. Additional digital logic is provided to be able to "force" a particular output. The internal design of the two FPU's is quite different, owing to the differing possibilities and restrictions of the technologies, however the functionality, as shown in Fig. 11, is similar.

In this chain the two outputs of the preamplifier were captured and multiplexed into a single ADC input. Each channel had its own logic cell array to serve as pipeline memory and local control. These LCAs were daisy-chained and controlled by a master LCA. Communication with the readout system was performed with a fiber-optic interface using three fibers: clock (down), command (down) and data (up).

Laboratory tests at 40 MHz with simulated preamplifier pulses indicate that the linearity is better than 0.1% over the full range. The noise of the ADC itself, in the actual implementation, was measured to be 0.5 LSB, or < 150 mV at the input.

The threshold, at which the FPU changes ranges, was common to all circuits and externally generated. This provides a means to "program" the amount of overlap between the ranges. In addition, as the pedestal levels were completely programmable, the energies at which the ranges changed could also be adjusted during the tests.

Results The results obtained in the test beam were:

- Excellent linearity: a linearity of better than 0.1% was observed both on the test bench with calibrated input pulses and in the test beam by splitting the signal and sampling

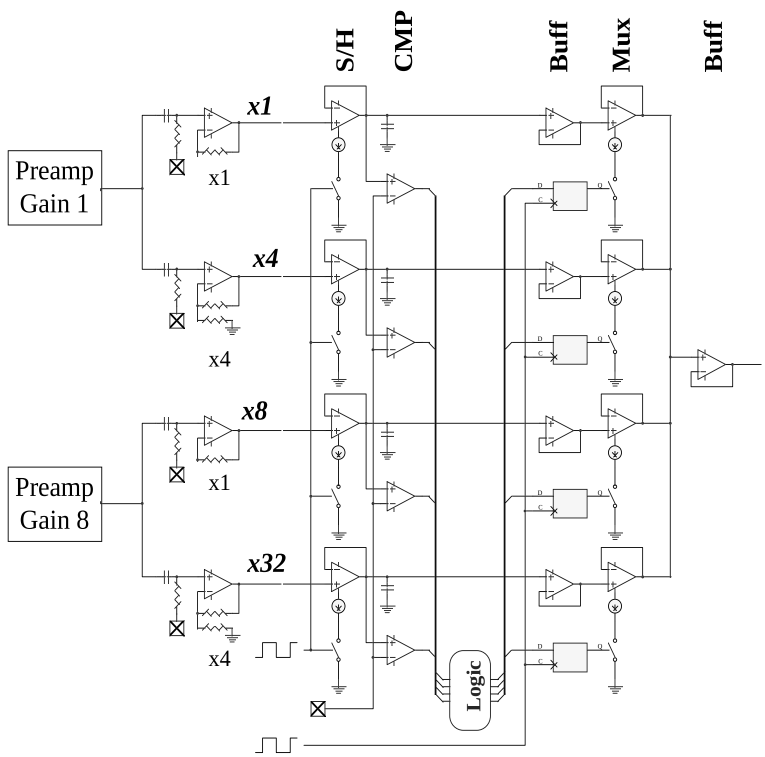


Figure 11: Schematic of the floating point front-end.

part with a conventional charge integrating ADC.

- Energy resolution: (up to noise) the energy resolutions obtained were independent of the electronics used: i.e. the same (or better) energy resolutions were obtained with full-speed, full-range readout as with conventional charge ADCs.

Different configurations did, however, have different noise contributions. These data are quite recent, and the precise mechanism of noise generation and coupling are not yet known. However, in all cases the noise observed in the charge ADC and the noise observed in the FADC were the same. This indicates that the noise was coupled through the front end, as it was common to both readouts. The lowest noise configuration was the FADC alone, with 120 MeV of noise in the sum. With the CHFET FPU, noise increased by a factor of 1.25, and with the BiCMOS FPU, noise increased by a factor of 1.7.

Conclusions of the 1996 electronics development This was the first attempt in the CMS ECAL to produce a realistic readout system that was capable of covering the full dynamic range at LHC speeds. All elements of the system will be refined in future iterations.

For the CHFET part, performance was limited by an unexpected flaw in the process restricting the operating range of the PFETs. This tended to limit the swing of the internal amplifiers, and thus the usable output range. As a result, the CHFET part displayed good performance up to energies of $\sim$30 GeV, but performance was significantly degraded at higher energies.

For the BiCMOS part, an underestimation of the load capacitance at the output of the chip resulted in an off-chip buffer that was too small, resulting in a 'delay' on the rising edge of the pulse, for very large input signals.

These problems will be addressed in the next iteration. In the BiCMOS case, the solution is straightforward, whereas in the CHFET case, some re-design is required.

Radiation Hardness The BiCMOS parts (preamplifier and FPU) lend themselves to natural translation into DMILL, and versions of the parts in DMILL are expected later this year. CHFET is known to be extremely radiation hard. In order to test parts for suitable radiation hardness in the CMS ECAL (1 MRad and 2.10^{13} n/cm^2 in 10 years at large η) we have performed tests at the PSI proton beam. The AD9042 was tested at equivalent doses of 2.2 MRad + 3.3×10^{13} n/cm^2 and a special CHFET test chip at equivalent doses of 1.4 MRad + 2.7×10^{13} n/cm2. Absolutely no change in performance of either part was observed at these doses.

Plans for 1997 and 1998 Based on the successful results of the 1996 electronics tests, the CMS ECAL group is proceeding to build a pre-prototype matrix for 1997. This matrix will be an attempt to combine the developments in electronics and mechanics in order to produce a small section of the final detector that is as realistic as possible in all aspects. For the electronics, Princeton will continue developments along the lines it has followed for the last two years, concentrating on the issues of signal acquisition and conversion, along with some of the associated mechanical problems. Specific goals for 1997 include

- An updated 0.8 micron BiCMOS FPU, currently in the design and layout stage to be submitted for fabrication in mid-November 1997 (in a non-rad-hard commercial process). Expected delivery in February 1997.
- Translation of the full BiCMOS FPU into DMILL (rad-hard) for submission in February 1997. Expected delivery in May 1997.
- Characterization and radiation hardness testing of the DMILL BiCMOS FPU test structure submitted in February 1996, which is expected in December 1996.
- Further characterization and modeling of the 0.7 micron CHFET process based on the test chips delivered in July 1996
- Development of a new CHFET FPU as well as further test structures for submission at the end of 1996 or the beginning of 1997
- Production of 36 channels of floating-point ADC (FPU+ADC) for the pre- prototype. This will be in two stages, first with the non-rad-hard version submitted in November, then with the two rad-hard versions (DMILL and CHFET)
- Studies of packaging using ceramic substrates for optimal heat transfer. Several different packaging developments are envisaged: one for the ADC part, one for the FPU part and a third for the associated analog functions. All of these packaged parts will be used in the pre-prototype
- Developments for mid to end 1997 will include a custom clock distribution chip, and first studies of rad-hard fiber optic transmission. In addition, in 1997 we will begin to address the questions associated with rad hard voltage regulation needed to supply and monitor power to the readout.

Monitoring Caltech is responsible for the Light Monitoring/Calibration system for ECAL. It is will be a precision light source and coupled to an optical distribution system which will supply light to the crystal super-modules for distribution to the individual crystals. The LSDS must provide light pulses with an intensity known to 0.2% to achieve a long term intercalibration precision of 0.3% [28].

Preliminary specification and a conceptual design of LSDS were defined in collaboration with the Saclay group in 1996.

FY'96 R&D Result In FY'96 the main R&D effort was devoted to understanding the technical requirements for the LSDS by systematically investigating the performance of $PbWO_4$ crystals. As a by-product, this crystal investigation has contributed to the progressive quality improvements for mass produced crystals. Samples from the Bogoroditsk

Techno-Chemical Plant (BTCP) and the Shanghai Institute of Ceramics (SIC) were systematically investigated. Part of the results of this investigation have been published in NIM and reported at different conferences [29]. This investigation is being carried out in close collaboration with the Brookhaven group and in conjunction with other CMS groups.

A number of conclusions of importance to the conceptual design of the LSDS can be drawn from this study.

- It was found that the scintillation mechanism in $PbWO_4$ crystals is not damaged by radiation, and the degradation in the light output was due only to radiation-induced absorption, i.e. color center formation. This was deduced from the facts that 1) no damage was found in the shape of the $PbWO_4$ emission spectrum; 2) no damage was found in the $PbWO_4$ decay kinetics; and 3) only small degradations were found in the light response uniformity for low doses (up to 10 krad), if the initial light attenuation length was long enough. This indicates that a fundamental condition for using light monitoring as a tool for inter-calibration is satisfied.

- It was observed and later confirmed at the CMS test beam that the light output of the crystal degrades noticeably after doses of only about 100 rad, and recovers on the timescale of a day.

Since doses at LHC are expected to be 100 – 1,000 rads per day, the intercalibration system should allow for continuous *in situ* operation. The LSDS is therefore designed to inject light pulses during the 3.17 μs gap in every 88.92 μs LHC machine cycle.

Because of the close relationship between the crystal monitoring and calibration requirements and the radiation damage, much effort was devoted to understanding the correlation between radiation damage and impurities and/or defects in the crystals. By using Glow Discharge Mass Spectroscopy we were the first to observe a quantitative correlation between the level of the trace element Molybdenum and the fraction of the slow component of the light emission, confirming a suggestion made by the Kobyashi group at KEK. The manufacturers subsequently produced crystals with low Mo concentrations and other cation contamination removed from the raw material and these new crystals showed a much reduced slow component.

However, there does seem to be no obvious correlation between a broad range of trace impurities and the crystals' susceptibility to radiation damage, suggesting that this effect may be caused by crystal defects, such as oxygen vacancies. This inference has been supported by measurements on four samples from SIC manufactured in different atmospheres: argon, air, oxygen and vacuum, and the samples annealed in oxygen and air were found to have better low-dose radiation hardness. This suggests that some compensation of the oxygen vacancies is effective in reducing the color centers in the crystals.

FY'97 Plan In FY'97, we will setup and test a monitor test bench. This will consist of crystal samples in a radiation environment illuminated by different light sources: laser, Xenon flash lamp, LED and laser diode through optical fibers. The main work will be carried out at γ-ray, hadron and neutron irradiation facilities in the US. It will be delivered afterwards to CERN for further laboratory and beam tests. The overall goal of this test bench is to establish the feasibility of the "Continuous Monitoring" as an inter-calibration method, and to define the technical parameters of LSDS.

The Caltech and BNL groups plan also to continue to study the correlations between radiation susceptibility and the point defects and impurities in crystals using material analysis, including an investigation of full size $PbWO_4$ samples to understand any changes in the optical properties under irradiation, to determine the role of inclusions. This will follow the same lines as has been done in the past in developing radiation resistant BGO and BaF, and as is currently being done for CsI(Tl).

Advanced Engineering for the Calorimeter The ECAL group at Lawrence Livermore National Laboratory (LLNL), have concentrated their efforts in FY'96 on two projects. These are the design and construction of a prototype cutter/polisher for the end faces of the $PbWO_4$ and the engineering design of the cooling and temperature monitoring of the crystals. Both these projects make use of the unique experience and capabilities of the LLNL group. We expect to continue these projects in FY'97 and to expand our role in the ECAL engineering program in FY'98.

Crystal End-Face Cutter/Polisher In the construction of the crystal calorimeter each crystal producer will be supplied by the collaboration with the necessary machinery to cut and polish the crystal surfaces. One of these instruments will be to cut and finish the end faces of the crystals; this process is both difficult and essential to do as the two ends are the first ends to be cut and are used as reference surfaces in the subsequent stages.

The role of the LLNL group is to design and construct a prototype cutter/polisher. When complete the cutter/polisher will be delivered to CERN with a complete set of documentation to allow the fabrication of a series of similar machines for shipment to the crystal fabrication plants. The LLNL group will be responsible for prototype development, its documentation and the transfer to our European collaborators. As crystal production will begin in 1999, it is essential that this project be complete by the middle of 1998.

A number of sample lead tungstate crystals were prepared and analyzed in FY'96. Two techniques were studied: Single Point Diamond Turning (SPDT) and loose abrasive lap polishing. SPDT studies were carried out at the urging of the ECAL Technical Board. However, due to variations in the crystal quality, results on SPDT remain inconclusive. For loose abrasive lapping, which we have advocated as a method for achieving highly polished surfaces with a minimum of induced stress in the surface and sub-surface, we have demonstrated that methods using both diamond and cerium oxide abrasives meet the specification for the CMS ECAL. Current efforts are now focused on identifying commercially available planetary polishers that can be adapted to LLNL-designed tooling to allow polishing of crystal end-faces. This work will continue into FY'97 with the procurement of a suitable machine and the design, fabrication and test of the end-face polishing system.

LLNL also performed measurements of lead tungstate mechanical properties including coefficient of thermal expansion, Young's Modulus and solubility measurements to assess toxicity of the lead tungstate during the cutting and polishing steps.

Thermal Design and Engineering Both the crystals and the APD's have temperature dependent responses, such that an increase in temperature decreases the response by approximately 2% for both devices. In order to meet the specification of a 0.5% constant term in the energy resolution the temperature of the crystal matrix and the APD has to be very well controlled.

The LLNL group is participating in the engineering effort to design the cooling and monitoring system. In 1996 a thermal finite element analysis (TFEA) based on preliminary cooling system designs proposed by CERN engineers was started and results presented to the ECAL group. This effort was useful as a means of demonstrating the power of TFEA for evaluating non-intuitive features of cooling systems that combine convective and conductive flow paths to achieve particular thermal environments.

The results of these calculations indicate that under reasonable cooling assumptions, the crystal can be maintained at a particular temperature with a small gradient of temperature only in the vicinity of the APD and temperature sensor. This result was useful for the electronics designers to see that placement of certain chips on the preamp board as well as the conductive paths that are established between the board and the cooling bar system are very important.

New designs are being proposed by the ECAL Design Group now that the mechanical and electronic systems are coming closer to final definition. LLNL will receive the next version of the mechanical/electronic design to model using TFEA in FY'97. We will make recommendations to the design team based on the results of this analysis in order to further optimize the design. We will also participate in the design of prototype cooling systems and measurements in order to benchmark the results from the TFEA.

Integration Engineering In FY'96, LLNL participated in preliminary engineering design reviews of different mechanical systems for the CMS ECAL. We found that our engineers can provide valuable integration expertise to the ECAL Design Group and we hope to begin applying ourselves more in FY'97 and FY'98 to the task of assisting the Design Group where necessary. In FY'97, our TFEA work will lead to a greater engineering involvement in the integration of the ECAL internal systems as well as the integration of the ECAL with other CMS sub-systems, in particular the CMS HCAL system.

Table 15: Electromagnetic Calorimeter FY 1997 Funding Request (K$).

WBS Number	Activity/Task Description	Institution(s)	FY'97 Req. DOE	FY'97 Req. NSF
4	**Electromagnetic Calorimeter**		**514**	**57**
	Photodetectors		**104**	**57**
	Subcontract to EG&G for APD	Minnesota	60	
	Device Evaluation	Minnesota	30	
	Device Evaluation	Northeastern		10
	APD Neutron Irradiation	Northeastern, Minnesota	9	27
	Domestic Travel	Northeastern		10
	APDs for test beams	Minnesota	5	
	APDs for test beams	Northeastern		10
	Electronics		**200**	**0**
	A to D converters for test beam	Princeton	20	
	GaAs CHFET FE Prototypes	Princeton	40	
	DMIL CMOS FE Prototypes	Princeton	40	
	Full Chain Development	Princeton	50	
	Engineer (4 months)	Princeton	50	
	Crystals and Monitoring		**210**	**0**
	Crystal Characterization	Caltech, BNL	45	
	Technician Salary	Caltech	40	
	Monitoring Light Source	Caltech		
	Crystal Endface Cutter	Minnesota	65	
	Crystal Matrix Thermal FEA	Minnesota	60	

3.5 Tracking System: Pixel Vertex Detector

A pixel vertex detector has been adopted as part of the CMS central tracking system, with the US taking responsibility for constructing the pixel endcap disks [4]. The overall development is directed by Roland Horisberger at PSI. The CMS management of the tracking effort is illustrated in Fig. 12. The general timeline for the project is shown in Fig. 13. Near-term CMS milestones for tracking and pixels are as follows:

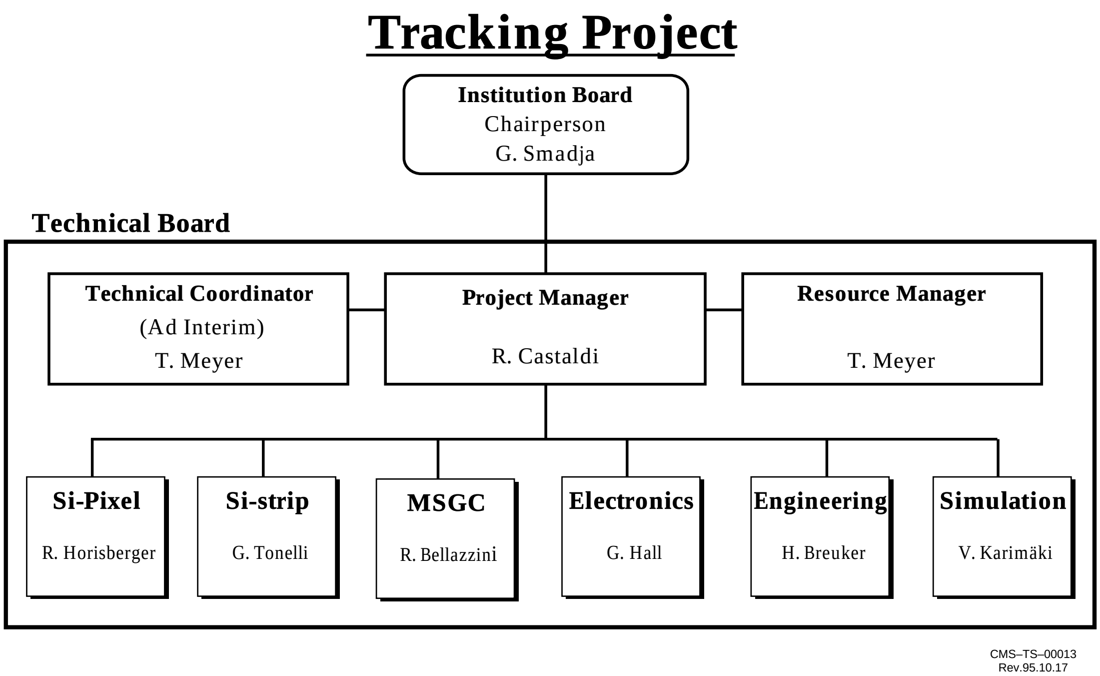


Figure 12: CMS Tracking Project organization.

- Tracking system
  - 12/97 Technical Design Report
- Pixel detectors
  - 12/97 Readout Architecture Decision
  - 12/97 Prototype module with LHC adequate analog block

A summary of the pixel FY'97 funding request is given in Table 16.

To achieve a strong and focused program, the US CMS tracking group has decided to concentrate entirely on the endcap pixel disks. The tracking group in US CMS has also been strengthened this year, with several additions. To meet the milestones above, we are now working directly with PSI on the design of the pixel analog block and the PSI "data drain"

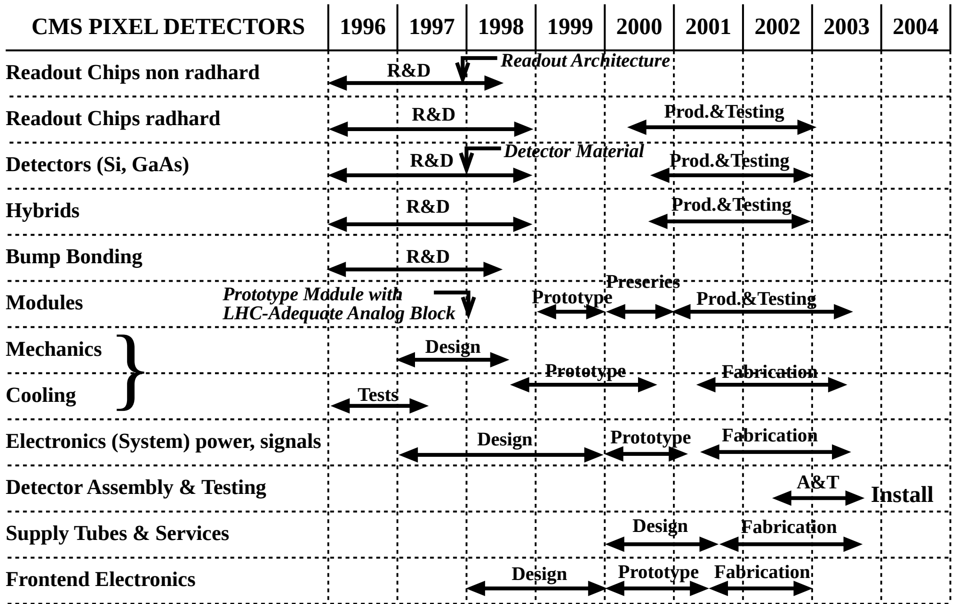


Figure 13: CMS Pixel Project Timeline with Near-Term Milestones.

readout architecture [30] rather than continuing to work with LBL on the pixel readout. This ensures a common pixel readout strategy for the barrel and endcap in CMS.

The goal of the forward pixel disks is to extend precision tracking and secondary vertex measurements out to η of order 2.5 (consistent with the rest of the forward detector) with at least two measurements on a track (one may be in the barrel). The Technical Proposal design has three disks per endcap (actually rings with 7.5 cm inner radius and 15 cm outer radius) and coverage to $\eta = 2.6$. A low luminosity configuration is now planned with a beam pipe of reduced radius and two pixel disks in each endcap instead of three. The active area of the disk nearest the barrel extends inward to a radius of 4.4 cm, while the other disk is the same as in the high luminosity configuration. The pixel disks must divide in half for insertion. Our immediate goal is to build the four pixel disks for this system.

Pixel Array Design Studies In the barrel, square pixels (125 x 125 μm^2) with analog readout are expected to achieve excellent impact parameter resolution in the $r\phi$ plane through the spreading of charge in the pixel sensor due to the Lorentz force in the 4 T CMS magnetic field. The z resolution is improved by arranging the pixels in a staggered, "brick wall" pattern. Since the pixel arrays of the vertical forward disks in the Technical Proposal have no Lorentz charge spreading, forward pixels are rectangular (50 x 300 μm^2) with the long dimension approximately radial to achieve sufficient impact parameter resolution in the $r\phi$ plane. This compromises the z resolution, however.

To remedy this, we have initiated a study of impact parameter resolution using analog readout as a function of pixel dimensions, aspect ratio, depletion depth and discriminator threshold. General simulation tools (full GEANT+CMS simulation, charge deposition in individual pixels, fluctuations, etc.) have been developed in the US (primarily at FSU/SCRI, UC Davis and JHU) for the forward pixel system. It is easily modified for study of variations of the geometrical configuration.

Preliminary simulations show that good results can be achieved with square pixels as in the barrel, particularly if the arrays are tilted away from the production vertex in the rz plane. The tilt angle increases the charge sharing between pixels adjacent in r proportional to $\tan(\theta_{track} + \theta_{tilt})$ while only increasing the detector area proportional to $1/\cos(\theta_{tilt})$. This charge sharing facilitates analog position interpolation in the radial direction. The tilt also introduces an angle between the solenoid magnetic field and the drift field in the detector, resulting in a significant Lorentz angle for the drifting charge carriers and sharing in the azimuthal direction as well. A further benefit is that one avoids the difficulty of providing p-stop isolation for pixel arrays with narrow pitch (*e.g.,* 50 μm). The pixels may be similar to or the same as the ones in the barrel.

In an (idealized) example, single, high momentum ($p_T = 20$ GeV/c) muon tracks were simulated in the forward detector with a tilt angle of 25°, a pixel threshold of 3 KeV (830 electron-hole pairs) and a depletion depth of 150 μm. The effect of the Lorentz angle was simulated but the pixels were not staggered and alignment errors were ignored. The predicted impact parameter resolutions for 100×100 μm^2 pixels were 31 μm in the $r\phi$ plane and 130 μm in z. The results for the (50×300 μm^2) pixels of the Technical Proposal were 27 μm and 320 μm, respectively.

The simulation study will be completed by the end of December, 1996. From this, one will determine the pixel size and shape giving the best position resolution. This information together with the number of pixel chips required, the material budget and funding constraints will determine the final detector geometry. It will be carried out primarily at FSU/SCRI.

Mechanical and Cooling To allow the pixel arrays to be split for insertion, a design based on wedges appears to have significant advantages over the arc structure shown in the Technical Proposal. The wedge design also allows one to construct the tilted pixel arrays referred to above. Fig. 14 shows a disk constructed of 24 overlapping, tilted radial wedges bearing pixel detector tiles similar to those of the Technical Proposal. Autocad drawings of different conceptual designs of the forward pixel wheels have been made at NU and supplied to HYTEC for detailed engineering studies. The support wedge may be a carbon composite structure with embedded cooling channels. In the figure, each wedge is rotated a fixed amount about its central radial axis in a turbine-blade configuration. It would also be possible to mount the wedges so they overlap alternately in front or in back without "turbining." In either case, the wedges can be supported by rings at the inner and outer radii. Cooling fluid (most likely binary ice) would enter and exit at the outer edge. Kapton cables and optical fibers would also be brought from the detector tiles to the outer periphery.

A double-scale mock-up of a wedge was constructed by the NU group to investigate assembly methods, cable routing paths, etc.

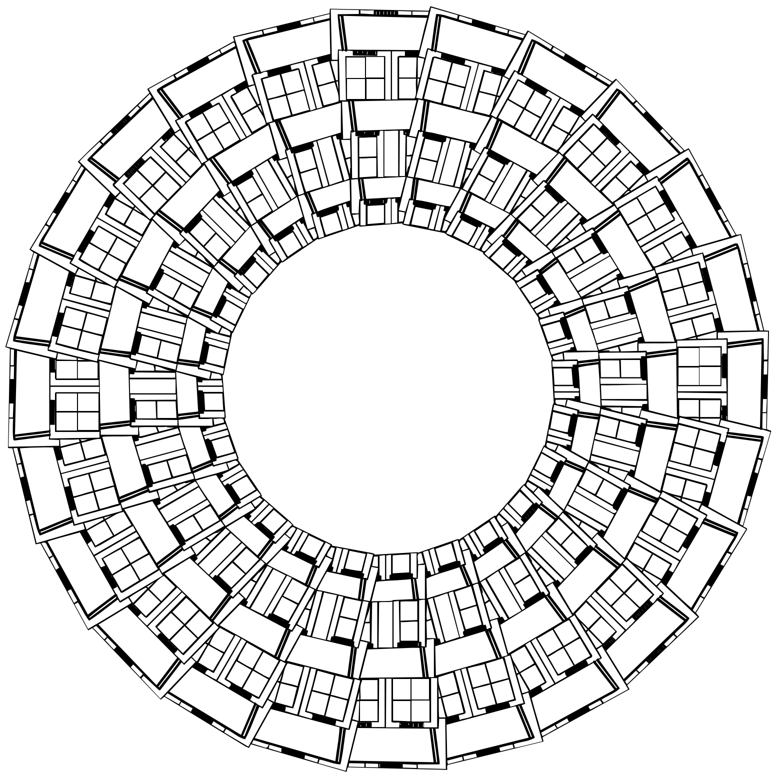


Figure 14: Pixel Forward Disk Constructed of Tilted Radial Wedges.

Monies for the proposed full engineering study of the mechanical supports and cooling for the pixel arrays were not available this year. To take maximum advantage of the funds available, initiation of the engineering study was delayed until the question of arc *vs.* wedge design was better understood. The engineering study has now been started with HYTEC, using a radial wedge as the basic unit. A finite element model will be developed for the wedge module with suitable restraints simulating the support structure to determine cooling channel sizing and assess mechanical performance. Alternative materials and design variations will be evaluated to reduce thermal strains and improve the stability of the detector while keeping radiation length to a minimum. The method of mounting ("turbine blade" *vs.* "overlap") will be examined, although the simulation of a full disk must await the second phase of the study. Initial cost estimates for wedge construction will also be provided. This study will be completed by Feb. 1, 1997 using current funds.

The goals for this study are as follows:

- Study stiffness of "blade" (maintain position to $5-10$ μm, including presence of cables and gravity).
- Optimize cooling (flow rates and cooling method) to achieve temperature uniformity of 2 C$^\circ$ or better over the surface of the "blade".

- Optimize above two conditions for minimum material budget.
- Suggest possible mounting techniques of pixel chips so that they can be removed.
- Supply preliminary cost estimate of “blade” construction.

FY’97 Requirements: Mechanical and Cooling

The second phase of the mechanical study must be completed by October 1, 1997 in order to prepare the Technical Design Report at the end of the year. The goals for HYTEC to address are as follows:

- Design support structure allowing to assemble ’blades’ into a wheel configuration maintaining the required position accuracy of $5 - 10$ μm.
- Suggest techniques for mounting the “blades” into wheels and for aligning them.
- Study cooling manifold implementation.
- Study mechanical stability of wheel considering presence of cables, cooling pipes, gravity, and the required splitting of the wheel for installation.
- Supply cost estimate of “wheel” construction.

Prototype modules must be constructed to verify the results of the calculations of the mechanical and cooling concepts.

The mechanical and cooling study will be carried out by HYTEC. Testing of mechanical properties of prototype modules will be carried out by NU and Fermilab. The cooling studies of prototypes will be undertaken by U of Miss. and Fermilab.

These activities will be the responsibility of NU for the mechanical aspects and U of Miss. for the cooling.

Pixel Readout

A goal for the past year was to investigate an analog front end design. We are now working closely with PSI on the pixel analog block and readout architecture rather than continuing to work with LBL. The PSI “data drain” architecture buffers analog pixel data on the column periphery rather than on the pixel itself. It also fits in well with the overall CMS analog fiber-optic data acquisition system and has significant overlap with previous readout development work at UC Davis.

UC Davis and Black Forest Engineering have designed an analog front end using specifications developed in collaboration with PSI for the CMS pixel analog block (suitable for the barrel as well as the disks). A test chip, referred to as SPAR-C, has been fabricated in the HP 0.5 μm CMOS process and is currently under test [31]. The specifications and preliminary test results are given in the table below. The specification parameters which have been measured are well within the requirements. The time walk for the trigger pixel is well within CMS specifications with automatic readout of neighbor cells for charge-sharing analog information.

SPAR-C CMS Analog Block Prototype Performance

Parameter	**Required**	**Goal**	**Measured**
Min. Signal Level	1500 e^-	1000 e^-	1000 e^-
Max. Leakage Current	100 nA	150 nA	Not Meas.
Timewalk (4K e^-)	< 25 ns	< 20 ns	< 14 ns
Threshold Sensitivity	1K – 4K e^-	—	1K – 4K e^-
Power Consumption	< 30 μW	—	Not Meas.
Input Dynamic Range	> 45K e^-	—	1K – 45K e^-
Input referred ENC	< 100 e^-	—	70 e^-
Maximum Pitch Dimension	< 50 μm	—	40 μm

FY'97 Activities and Requirements: Readout

In order to meet the overall CMS pixel detector milestones at the end of 1997, pixel readout test structures must be fabricated and tested. These include a prototype readout column array and a larger two-dimensional array for bonding to a pixel sensor. Conversion to the radiation-hard Honeywell SoI process must also be undertaken in FY'97 for comparison with devices produced in Europe in other rad-hard processes.

The timeline for the readout development in FY'97 is:

Date	**Milestone**
2/97	Double column prototype submission
5/97	Double column fabricated
7/97	Bench test
8/97	Test with bonded sensor
8/97	Rad-hard conversion of front end
8/97	Prototype readout 2-D array layout
11/97	Rad-hard chip fabricated
11/97	Prototype 2-D array fabricated

Note that fabrication of the rad-hard chip and the 2-D array were postponed until the beginning of FY'98 due to lack of sufficient funding in FY'97.

These activities will be the responsibility of UC Davis.

Hybridization Significant progress has been made in bump-bonding in the lab at UCD. We have successfully bonded test chips with indium bumps and have achieved the required high yield per bump (greater than 99.74%). The operation is sufficiently rapid that we estimate that the pixel detectors for the experiment could be bonded in a period of approximately one year.

These results come from a small batch of chips, however. A larger batch must be run in order to obtain production-mode yield and reliability numbers. Pixel pitches of 100 μm and 50 μm will be tested as representative of the range of values likely to be employed. Pb/Sn solder must be tested as an alternative to indium, and epoxy wicking for mechanical strength with indium must be investigated. A prototype module consisting of a readout using the new analog block bonded to a sensor array will be tested in a particle beam. The milestones for this program are given below.

Date	Milestone
11/96	Start bump-test mask design
6/97	First 100 In modules tested
8/97	Pb/Sn modules tested
8/97	Test readout with bonded sensor
9/97	300 In modules tested

This program will be the responsibility of UC Davis.

NSF Program Funding for roughly 40% of the US CMS tracking project is being sought from the NSF. The following items (sensor arrays, local communication chip, Kapton cables, optical data transmission) have been described in greater detail in the CMS Detector R&D Proposal to the NSF [2]. Key items and milestones are summarized below. The responsible institution is JHU in all cases. Irradiation and some beam tests will take place at Fermilab, with the involvement of Fermilab collaborators.

Sensor Arrays

The pixel sensor array must function in a partially depleted mode after being exposed to fluences approaching 10^{15} p/cm^2, equivalent to several years of operation at LHC for the inner pixels. This imposes a severe constraint on the design of the pixel array, requiring detailed studies of prototype detectors to asses bulk damage, pixel isolation, charge collection, noise, cross-talk, etc.

Limited funding prevented us from fabricating pixel arrays in the past year. In spite of this, sensor performance studies were begun using 16×16-pixel arrays from PSI. These arrays have a connection from each pixel to a wire bond pad along one edge. They were connected to VA2 readout chips via a stripline to allow irradiation of the pixels without damage to the readout chip. A beam test prior to irradiation was carried out at CERN by JHU physicists and S. Kwan of Fermilab in September, 1996 using the beam telescope system and DAQ developed at CERN by JHU.

FY'97 Activities and Requirements: Sensor Arrays

The milestones and timelines require that sensor radiation damage studies take place in 1997. Sensor arrays must also be fabricated for completion of the prototype module.

- Pixel radiation test. Tests will begin at the Booster of FNAL in Fall, 1996. They will be irradiated to 10^{14}protons/cm^2, followed by a beam test. This process will go through several iterations to reach the full fluence required. This is to be completed for 16×16 arrays in Spring 1997.

- 24×32 pixel array to test readout design. This design will be based on the radiation tests described above and the optimization from Monte Carlo simulation. It will be completed in 1997 and tested with pixel readout chips.

Associated Signal Handling: The Local Communication Chip (LCC) is an interface between several readout chips and an Optical Transmitter/Receiver connected to a remote VME card via optical fibers. The detector diode arrays provide signal and power bussing from the bump-bonded readout chips (and possibly the LCC itself) to wire bond pads at one edge of the detector for connection to the kapton cable. Specifications and at least preliminary designs must be developed for the Technical Design Report at the end of 1997.

- *Design of Local Communication Chips (LCC)*
  The LCC handles communication between the pixel readout chips and the optical transmitter. Both of them are still evolving. So there will be several iterations.

1996	Fall.	specification will be completed
1997	Jan.	design of first prototype complete, submission to MOSIS for fabrication
	Apr.	first prototype testing
		more iterations
	Fall	prototype complete for Technical Design Report (TDR)

- *Kapton cable connection*

1996	Fall	Specification complete
1997	Summer	prototype fabricated

- *Optical Transmitter*
  The design and fabrication of front end electronics of all CMS subdetectors take on a common approach by the same group of people, except the pixel system – because of its special nature and enormous number of channels involved. We will follow and test the common design of Optical transmitters and develop necessary modifications for the pixels.

- *Optical fiber*
  Communication between optical transmitters and the VME is carried by optical fiber for all subdetectors. We will follow the standard CMS design with necessary modifications.

3.5.1 Pixel Tracker FY 1997 Funding Request

A summary of the FY'97 funding request for the pixel tracking efforts is given in Table 16.

Table 16: Tracking FY 1997 Funding Request (K$).

WBS Number	Activity/Task Description	Institution(s)	FY'97 Req. DOE	NSF
5	**Tracking System**		**293**	**130**
	Pixel Tracker		**293**	**130**
	Diode Arrays		**0**	**83**
5.1.1.1	Diode array design/fabrication/test	Johns Hopkins		83
	Pixel Off-Chip Signal Handling		**0**	**47**
5.1.2.2	LCC development	Johns Hopkins		33
5.1.3.1	Kapton cable development	Johns Hopkins		8
5.1.3.2	Optical transmitter development	Johns Hopkins		6
	Pixel Readout		**137**	**0**
5.1.2.1	Double column prototype layout/fab/test	UC Davis	72	
5.1.2.1	Readout array layout	UC Davis	38	
5.1.2.1	Rad-hard conversion of Front-end	UC Davis	27	
	Hybridization		**60**	**0**
5.1.4.1	Test wafers and metallization	UC Davis	3	
5.1.4.1	Indium bump testing for production yield	UC Davis	25	
5.1.4.1	Pb/Sn testing	UC Davis	20	
5.1.2.1	Tests with readout	UC Davis	12	
	Mechanical Structure and Cooling		**86**	**0**
5.1.3.3	Support and Cooling Engr Studies	Northwestern	71	
5.1.3.3	Support and Cooling Test Structures	Mississippi	15	
	Radiation Testing Studies		**10**	**0**
5.1.1.1	Test rigs and n irradiation tests	Fermilab	10	

3.6 Common Projects

The CMS experiment has items which are necessary for its success which are beyond the capabilities of any individual group within CMS. Most notably, in CMS these include the magnet systems; coil, coil vacuum tank, barrel and endcap steel return yoke; and portions of the offline system. These items are "Common Projects" within CMS and correspond to 26.2% of the total cost of the CMS experiment, or 28.5% of the "income" less infrastructure costs.

These items are the collective responsibility of the CMS Collaboration. For the US CMS groups, the cost of Common Projects is held at 28.5% of the US CMS contribution to CMS based on the CMS Cost Book version 7.0 estimate. This contribution is in European accounting, which, approximately, means that only M&S costs are accounted for. A 1.3 CHF/$ conversion factor is assumed. We treat these costs as the equivalent of purchase requisitions which total to the specified dollar amount. Therefore, they are assigned basically zero contingency, labor, and EDIA costs.

The goal of US CMS is to make in kind contributions in Common Projects, so that there is no, or virtually no, cash payment to CMS. At present, US CMS is involved in two efforts which arise from our leadership roles in the HCAL and EMU systems. The costs of these two efforts approximately saturate our Common Project contributions. In HCAL we are supported by the barrel solenoid coil vacuum tank. Therefore, we have been involved in the interface of the vacuum tank and HCAL *ab initio*. It is natural to take responsibility for procurement of the vacuum tank in this situation. For EMU we have been involved in the endcap steel design from the beginning since the EMU CSCs are supported on the steel, as is the endcap HCAL, HE, for which we have managerial and construction (transducer and readout) responsibility.

The EDIA for Common Projects, if new hires are required, appears as a Cost Book item. Thus, Common Project expenditures are incurred given the engineering efforts by US CMS on the vacuum tank and the endcap steel. In particular, the University of Wisconsin Physical Sciences Laboratory, because of its unique expertise, was asked by CMS to undertake engineering studies for the endcap steel yoke.

At present the exact responsibilities of the US CMS Collaboration are not defined for Common Projects. However, we note that the desire to make in kind contributions implies a front loaded cost profile since Common Projects are, in CMS, critical path items. Although the responsibilities are not yet clear, we assume that US CMS is responsible for the endcap steel and the vacuum tank. That assumption, and the CMS schedule, imply a cost profile for common projects as given later in Section 6. For the purpose of understanding CMS management and the US role in it, in Fig. 15 we show the organization chart of the Magnet Technical Board.

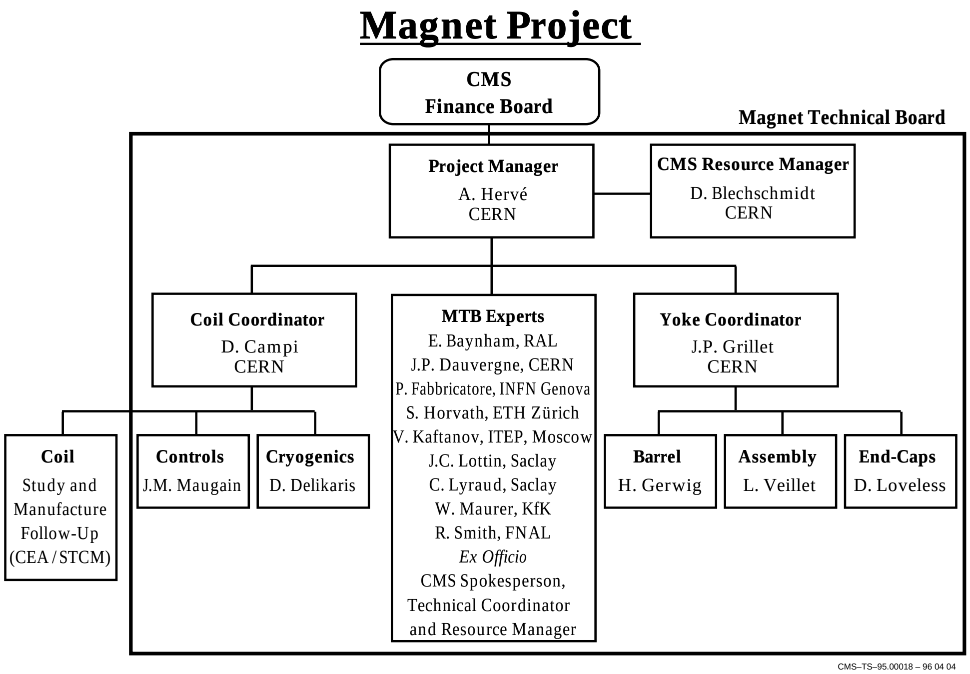


Figure 15: CMS Magnet Technical Board.

3.6.1 The Solenoid Vacuum Tank

As seen in the section above, Rich Smith, a FNAL physicist with experience in magnets, e.g. the D0 upgrade solenoid, is a member of the CMS Magnet Project. As US CMS groups have HCAL project management responsibility, we are clearly tightly connected to the vacuum tank. In 1996 R. Smith has been participating in the discussions for conductor fabrication. The decision in 1996 to use soft solder and perhaps then wind the coil in situ in the Assembly Hall, has simplified the coil project.

We have also used the Fermilab Purchasing Department to involve US firms in the Market Survey for the CMS coil. The US CMS Project Office intends to continue to involve US industry in all CMS Market Surveys and bids to the fullest extent. For example, the market Survey for the barrel iron yoke and the coil vacuum tank recently went out (March 1996) to US firms. The US CMS Project Office is committed to enabling US industry to participate in CMS “world wide bids”. In turn, CMS has committed the collaboration to free and unrestricted bidding by world industry for all CMS contracts.

In addition, FNAL engineers, e.g. Bob Wands, have been heavily involved in the mechanical engineering aspects of the vacuum tank. The Finite Element Analysis (FEA) done at Fermilab has lead to a stiffening of the vacuum tank and a 1996 redesign of the structure. In particular, deflections of the tank caused by the insertion of the HCAL make this study a natural area to bring US expertise to bear. This work was presented by Fermilab engineers at the 1996 CMS Magnet Preliminary Design Review (PDR).

Recently, the US facility in Florida, the National High Magnet Field Lab (NHMFL) has expressed interest in participation in the CMS magnet program. In fact, NHMFL has been invited to nominate a member for the CMS Magnet Technical Board. The US CMS Project Management has very strongly encouraged and supported the participation of US laboratories outside those focussed on HEP.

3.6.2 Endcap Disk Design

Introduction The endcap iron disks return the magnetic flux from the 4 tesla CMS magnetic field as well as providing many interaction layers of absorption. The return flux generates the major design problem for the disks. The total magnetic force on YE1, the first disk, is 48MN (4915 tons) and on the nose 17 MN (1700 tons). These are enormous loads compared to the weights (YE1 = 700 tons, nose = 160 tons). Our axisymmetric structural analysis shows deflections of 5 mm at the inner edge of YE1 due to these large forces. The second disk, YE2, (supported only at the outer edge) also has 5mm deflection. Our major design problem is to fabricate these disks (14m diameter, 60cm thickness, 700 tonnes) from smaller blocks and provide sufficient connection.

During the year many design studies were done by the shielding and calorimeter people to optimize the split between barrel and endcap calorimeter modules. The optimal split was to have a 300-tonne endcap module supported by YE1 so another major design effort centered on how to support this huge cantilevered load in the available space.

Accomplishments in '96

Preliminary Design Review On 7-8 October '96 CERN conducted a Preliminary Design Review at CERN for the magnet, which includes both the superconducting coil and the iron flux return. A CERN report provides the details of the review.

Magnetic Field calculation The axisymmetric field calculation (ANSYS) was updated as the geometry changed and estimates were made of the field in the area of the electronic racks on the outside of the detector (500gauss) and in the counting house (15gauss) where much of the trigger and readout electronics is located. From the field values the forces were derived and input to the subsequent analysis programs.

Structural analysis A full 3-D analysis program was developed which incorporated all the disk connections (struts at outer edges, compressive supports at inner edge), disk support, and mechanical loads. This model assumes the disk is composed of 24 sectors mechanically connected at 5 radii. Aside from the weight of the disks (floor slope of 1.23% added in worst case) the mechanical loads were the magnetic loading from the field and the large 300-tonne endcap calorimeter which is cantilevered from the first disk, YE1. This analysis proceeded in conjunction with the design of the YE1 cart and was essential to refining the cart design.

The main purposes of this analysis are to (1) estimate stresses on connections between disk segments when the disk is loaded magnetically and (2) estimate stresses and deflections in the carts supporting the three disks. Two versions have been investigated:

- **gravity loads only -** The predicted z deflection is 26mm at the top of the disk. Some of this deflection can be compensated by adjusting the cart supports, but some of the deflection comes from bending of the 60cm thick disk. This bending will need to be accommodated by adjusting the length of the z-supports attaching the endcap to the barrel return yoke. The maximum stress in the cart is 120MPa, which is safely below the yield point of 248MPa.
- **magnetic and gravitation loads -** In this model the endcap is connected tightly to the barrel yoke by the z-supports. The maximum deflection at the inner edge of YE1 is 7mm toward the center of the coil, which is slightly larger than the estimate for a solid disk. The outside of the YE1 is distorted 4mm away from the center of the coil, as the YE1 disk essentially pivots and distorts on the z-supports. The sector connection loads are roughly 3MN and vary slightly as a function of radius. The maximum tie rod (connecting the nose the YE1) force is 1.8MN; the maximum z-support force is 3.7MN and the average is 3.5MN. The maximum stress in the sector blocks occurs at the inner edge where an additional ring of alloy steel will be required. The maximum shear load for this ring is 2.1MN (or 267MPa).

Disk Fabrication The first plan to fabricate the disks envisioned electroslag welding. In Dec '94 we performed a welding test at SMS-Schloeman-Siemag mill in Germany. Both welds cracked during cooling so we scheduled additional tests at the Welding Institute in Aachen. These tests were carried out on 14-15 Oct. '96 and we are awaiting the results.

As a result of the failure of the first welding test we have actively pursued an alternate design which calls for mechanical connections. The most appealing geometry has 20 to 24 sectors arranged so the magnetic force is perpendicular to the connection. We have developed a reference design using tie plates and pins, but expect that a chosen vendor might choose an alternate form of connection. Using the results of the analysis we can specify the forces which must be accommodated.

The assembly of the disk can be accomplished vertically by machining semicircular slots in each of the sectors to locate the next sector. As each sector is rigged into place, the sector plate connections are reamed to fit and the necessary pins are installed. It is crucial that these sector connections have no looseness or play so we anticipate critical specifications on these pins.

Endcap Calorimeter Support As described in the introduction we need to support a 300-tonne endcap calorimeter cantilevered from the YE1 disk. Our analysis shows that a 10cm thick cone attaching the inner edges of each element is sufficient to provide support. Of course, good connections on the outer edge of the nose are also required.

This calorimeter will be designed and built in Russia so the interface needs to be specified. With the help of the 3-D analysis we have developed a plan for connecting the cantilevered load and have agreed with the Russian designers on a outline for the interface.

Disk Support During this year we have spent considerable effort to design a cart for YE1 which can handle the cantilevered load in the available space. The present YE1 cart is roughly 12 meters wide and weighs 60-tonnes. This width conflicts with slots in the floor and modifications are in progress.

The original design called for the YE1 and YE3 carts to move on the inner rails. Due to a conflict with the Very Forward Calorimeter the design was changed so both YE1 and YE3 carts now move on the outer rails. At this time our baseline design calls for Hilman rollers for moving the carts. However, there is a possibility of using air pads operating at 30bar. CERN has purchased 4 such air pads and tests will be conducted at CERN during fall and winter '96.

We have outlined a set of jacks and grease pads to provide the ability to move the large disks both vertically and transversely. The clearance between the endcap and the barrel was originally specified as 5cm but it seems likely this clearance will be smaller. As a result we clearly need to provide the possibility of adjusting the pitch, yaw, and location of these large disks to ensure the endcap can open and close.

Site visits During the last few years the Wisconsin group has visited many potential vendors including Creusot-Loire in France, Lukens and Precision Component in USA, Izhora in St. Petersburg, and several mills in China. At each site we discuss the project and attempt to evaluate the companies' ability to produce the quantity and the quality of steel that we need. By far the most important criteria is the ability to roll 60cm plate but the ability to machine large pieces cheaply is also crucial. It is important to us that a trial assembly be made in the factory and all connections checked out before shipping to CERN.

Plans for '97 The present CMS schedule requires us to begin assembling the first endcap at the end of '99. To keep to this schedule will require considerable effort during '97. Complete drawings of some items will be needed by the end of '97 and the outline of the entire endcap must be clear and conflicts resolved.

In Feb. '97 the magnet has a Technical Design Review at CERN which requires a full TDR document detailing the design and the operations of the endcap.

In summer of '97 we plan to send out a market survey from CERN to determine which vendors are (1) capable and (2) interested in the job. Then we plan to have a reference design ready by early 1998 when the call for bids would be sent out to interested parties. Because few vendors have the ability to roll 60cm plate we expect to break up the bid request into pieces such as (1) 60cm plate (2) 25cm plate (for YE3) (3) carts (4) installation. We anticipate that contracts for some (or all) the iron blocks and carts will be signed by summer '98.

3.7 Project Management

The US CMS Collaboration will, one hopes, begin a construction project in FY'98. That starting date is required in order to maintain the overall CMS schedule. To that end a bare bones project office is to be set up at Fermilab which will act as the "host laboratory" for the US CMS Project. The organization of the US CMS Project Office, which is foreseen to attain full staffing in FY'00, is shown in Fig. 16. A first step was taken in FY'95 with the establishment of a CMS Department in the Research Division of Fermilab. Partial support is provided by Fermilab as "host laboratory".

The steps taken in FY'96 were to coordinate the FY'96 funding request, to assemble the US part of the IMOU [3], to finalize a Project Management Plan [5] and associated US CMS Memoranda of Understanding (MOU), to setup templates for the revised Project Work Breakdown Structure (WBS), and to coordinate this document, the US CMS FY 1997 Project Status Report. All these sorts of activities must intensify in FY'97 if the US CMS Project is to begin in FY'98.

In particular, secretarial assistance has become a pressing issue. It is also necessary in FY'97 to continue integrating the cost and the schedule, given that a set of milestones now exists. The liaison to the parent effort of CMS at CERN also requires the expenditure of resources. For example, the coupling of the US CMS WBS and the CMS Cost Estimate [32] is very tight. For those subsystems where the US groups have complete responsibility it is, indeed, a one-to-one mapping. Maintaining that coupling is a nontrivial exercise. For example, Microsoft Project has been adopted and learned as the planning tool by all US CMS managers. Other agreed upon common software includes AutoCAD (mechanical engineering), Microsoft Word and Microsoft Excel. The FY'97 R&D request for US CMS Project Management activities is shown in Table 17.

In FY'97 US CMS intends to initiate an education and outreach section of the Project Management Office. Marge Bardeen of the Fermilab Education Office, who has extensive experience in educational matters, serves as the Fermilab liaison. The US CMS Collaboration has already launched a search for the Education/Outreach Coordinator.

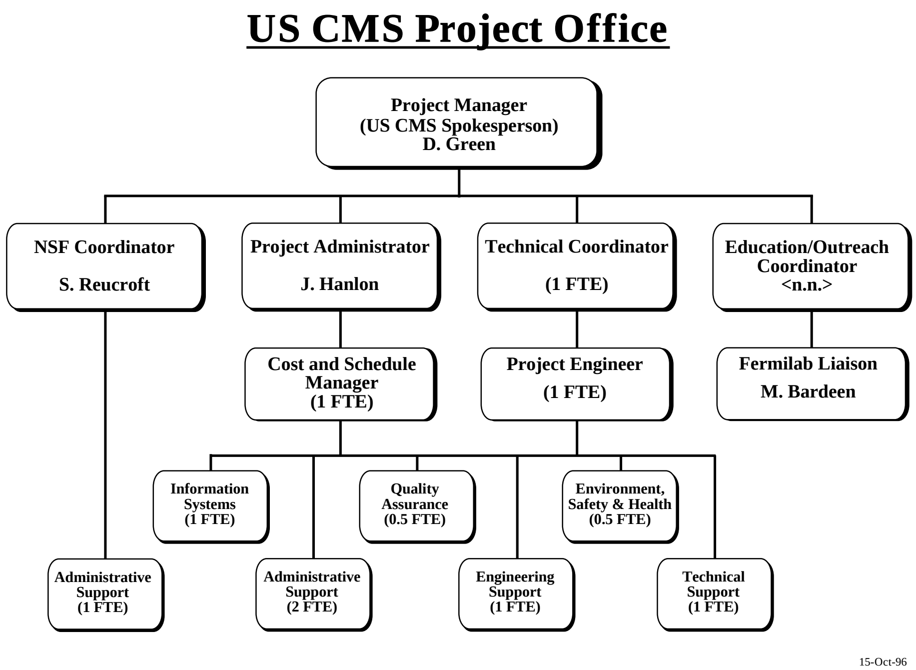


Figure 16: US CMS Project Office organization.

Table 17: Project Management FY 1997 Funding Request (K$).

WBS Number	Activity/Task Description	Institution(s)	FY'97 Req.	
			DOE	NSF
7	**Project Management**		**110**	**192**
7.1.1	Coordination and Planning	Fermilab	22	
7.1.2	Cost and Schedule Management	Fermilab	33	
7.1.3	Information Systems	Fermilab	23	
7.1.4	Administrative Support	Fermilab	32	
7.1.5	NSF Administration	Northeastern		192

3.8 Software and Computing

The CMS organization chart for the Software Technical Board is shown in Fig. 17.

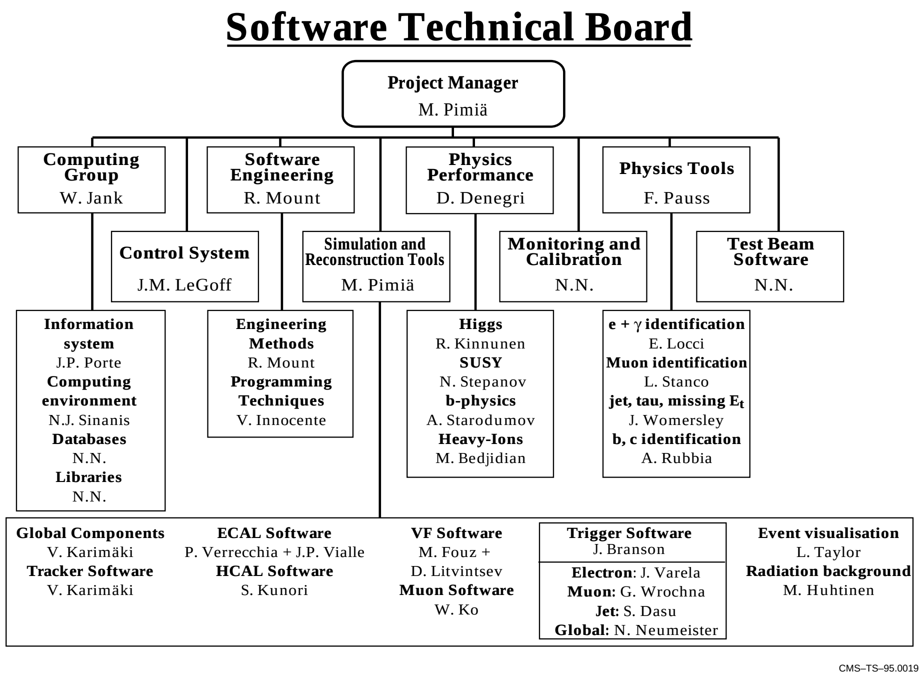


Figure 17: CMS Software Technical Board.

3.8.1 Progress and Status of R&D in FY 1996

The US CMS Software and Computing Plan has been developed and is included here as Appendix A. We will not repeat ourselves except to list the CMS Technical Notes generated by the US groups during FY 1996 in the areas of software and physics studies.

- Implementation of the CMDB file-based database system in CMSIM. L. Taylor CMS TN/95-171.
- Interactive Graphics for the CMS Experiment at the LHC. L. Taylor CMS TN/95-172.
- Strongly Interacting WW Scattering in CMS. J. R. Smith CMS TN/95-179.
- Comments on the Simulation of Background for the CMS Muon System. Yu. V. Fisyak and R. Breedon. CMS TN/96-019.
- Upsilon Suppression in Pb+Pb Collisions at LHC R. Vogt. CMS TN/96-041.

- Simultaneous Search for Two Higgs Bosons of Minimal Supersymmetry at LHC. H. Baer, C. Kao, X. Tata, et al. CMS TN/96-049.
- Missing Et P jets Signal foe Supersymmetry in the CMS Detector at the LHC. I. Gaines, D. Green, J. Marraffino, J. Womersley, W. Wu, S. Kunori. CMS TN/96-058.
- Searching for Dark Matter with the Future LHC Accelerator at CERN using the CMS Detector. V. Hagopian, H. Baer. CMS TN/96-065.
- Finding Tracks D. Adams CMS TN/96-66.
- CSC Detector Simulation in CMSIM 100. Jeff Rowe. CMS TN/96-68.
- CSC Trigger Simulation in CMSIM 100. Jeff Rowe. CMS TN/96-69.
- Evaluation of the CMS Muon Endcap Shielding. Yu.V. Fisyak. CMS TN/96-076.
- CMKIN – The CMS Kinematics Interface Package L. Taylor CMS TN/96-099.
- Design and Test of an Object Oriented Model for CMS track Reconstruction. I. Gaines et al. CMS TN/96-122.

In addition, there are progress in computing and network. These activities include Fermilab's beginning of a collaboration with CERN on the Data Model and Caltech's effort in packet-videoconferencing and other network issues.

3.8.2 Program for FY 1997

The software milestones for FY 1997 and the short term plan for software and computing are detailed in the Software and Computing Plan. Emphasis here is on the supplemental request for software and computing travel as shown in Section 4.

- The highest priority for software is to support optimization of subdetectors in their preparation for their respective Technical Design Reports, most of which are due by the end of 1997.
- Software Workshops, mostly held in CERN, remain effective for common software development and software-coordination. The Radiation Working Group, which also meets at CERN, is vital for the understanding and reduction of background – perhaps the most challenging experimental issue at LHC.
- An effective network is at the center of all computing models. Travel is required to develop and implement the means for efficient network access and management involving the US-CERN transatlantic link. In addition to efficient access to and from Fermilab by individual US physicists, the network developments also will be aimed at effective integration of the Fermilab and CERN efforts to carry out organized simulation, reconstruction and data access and distribution. These production-oriented tasks will require network tools that allow remote monitoring and control over networks, while maintaining sufficient security.

4 Supplemental Travel Request

In addition to the costs for M&S and labor needed for US CMS in FY'97, there are supplemental costs for travel and salary support of physicists. These costs are not part of the WBS as already explained in Section 3 of this document.

US physicists play critical roles in the management of the CMS experiment. We hold project management responsibility for the EMU, HCAL and Trigger subsystems. In addition, as indicated in Section 3, US physicists are Institutional Board Chairs for the Muon, HCAL, and Trigger/DAQ subsystems. We are also Technical Coordinators for the EMU and HB subsystems, and Resource Coordinator for HCAL. In ECAL, US physicists are task leaders for Crystal Processing and for Electronics and Trigger. In the area of Software and Computing, US physicists are coordinators for Muon, HCAL, and Trigger Software, for Event Visualization, and for Software Engineering.

In order to fulfill these responsibilities within an international collaboration such as CMS, travel support is sorely needed. Although we are pressing the teleconferencing technology, there remains an irreducible travel component to the operation of the CMS Collaboration. All subsystems in CMS also have an active test beam program, both at CERN and at other laboratories and facilities (e.g., Co^{60} radiation sources). Thus, travel funds are also needed in order to achieve our test beam goals.

A summary table of costs for travel broken down by subsystem and further by task is given in Table 18. Also indicated are the US CMS institutions involved. This table summarizes by university the travel requests already shown in Section 3 where the context of the tasks is available. The funding request summary for all FY'97 requests is given in Section 1. We request these funds simply in order to allow us to fulfill our positions of authority and responsibility within CMS.

Table 18: US CMS FY 1997 Supplemental University Travel Request to DOE (K$).

Subsystem/Task Description	Institution	Travel Request
US CMS FY 1997 Supplemental University Travel Request		**300**
Endcap Muon Detector		**75**
Simulations	UC Davis	5
Trigger front end	UCLA	12.5
P1 tests at FNAL	Carnegie Mellon	5
P1 tests at FNAL	Florida	15
P1 tests at FNAL	Ohio State	10
P1 tests at FNAL	Purdue D	10
Trigger front end	Rice	2.5
Steel design, integration	Wisconsin	15
Hadron Calorimeter		**75**
HF engineering	Boston	4
HB electronics	UCLA	3
HF optics	Fairfield	5
HB optics	Florida State	5
HB calibration/integration	Iowa	14
HB engineering	Maryland	11
HB engineering	Mississippi	5
HB calibration	Purdue G	5
HB optics	Rochester	11
HB phototdetectors	Minnesota	7
HF integration	Texas Tech	5
Trigger and Data Acquisition		**35**
Muon trigger	Rice	6
Muon trigger	UCLA	6
DAQ design	UC San Diego	10
DAQ design	MIT	6
DAQ design	Mississippi	1
Calorimeter trigger	Wisconsin	6
Electromagnetic Calorimeter		**45**
Travel for crystal characterization	Caltech	15
Travel for transducer evaluation	Minnesota	15
Electronics travel	Princeton	15
Tracking System		**35**
Pixel readout	UC Davis	17
Pixel mechanics/cooling	Mississippi	4
Pixel mechanics/cooling	Northwestern	10
Pixel tests	Purdue G	2
Pixel mechanics/cooling	Texas Tech	2
Software and Computing		**35**
Software coordination	UC Davis	6
Muon Software	UC Davis	10
Radiation Working Group	UC Davis	4
Computing model	Caltech	5
Inner tracker software/computing	Florida State (SCRI)	2
HCAL software/computing	Maryland	4
Inner tracker software/computing	Rice	4

5 WBS for the US CMS Project

First let us delineate the responsibilities of the US CMS Collaboration. In Fig. 18 is shown the managerial responsibilities of US CMS, while in Fig. 19 the construction responsibilities of the US collaboration are indicated. Basically US CMS is responsible for:

1. All the forward silicon pixel detectors.
2. ECAL transducers, very front end electronics and monitoring.
3. Barrel HCAL absorber and scintillator and barrel, endcap, and forward transducers and electronics.
4. Endcap muon cathode strip chambers.
5. Luminosity monitoring, level 1 calorimeter and forward muon trigger and half of the event building switch.
6. Common projects, presently thought to be the endcap steel return yoke and the barrel solenoid vacuum tank.

The summary WBS for these construction deliverables is shown in Table 19. The total project cost (TPC) is defined by guidance of the funding agencies to be approximately $173 M in as spent dollars. Prior years R&D is subtracted and escalation is removed using the profile supplied by DOE/NSF, and the yearly escalation rate supplied by DOE. The resulting funding profile, in FY'96 dollars, is shown in Fig. 20 The resulting WBS figures are given in this year (FY'96) dollars as the total estimated cost (TEC).

The NSF and DOE components of the TEC are attached to specific WBS items, as is shown later in this section. The quoted M&S costs are given for each subsystem, for the Common Projects, and (explicitly) for Project Management. The level 3 computing farm appears explicitly in Trigger/DAQ but offline software/computing is not part of the US CMS detector construction project, as is the case for CDF, D0, BaBar, and CMS proper.

We have assumed that M&S purchases can be obtained with essentially no overhead. In contrast, labor rates are taken to be the fully encumbered salary rate at the institution in question, if known. If not known, "generic" university or laboratory rates (with indirects included) were used. The same situation obtains for EDIA rates. The base cost is then defined to be M&S plus labor plus EDIA. The contingency was computed using quite standard project methodology at WBS level 5 [33]. The global rate is 27% of the base cost. Note that common projects, treated here as simple in kind purchases, have no assigned contingency. The base cost plus contingency is then the TEC.

Note that the US CMS project takes "European Accounting", using M&S costs as the European basis. The US cost credited by CMS is, roughly, 1.3 CHF/$ times the M&S cost given in the WBS table. Thus the US CMS credited contribution to CMS is $\sim$105 MCHF in "European Accounting". In CMS, the common project cost is taken to be 28.5% of the total contribution, or ~30 MCHF. Thus, the common project cost is ~30 M\$/1.3 = 23 M\$, or ~12% of the TEC.

The issue of "incremental overhead" is not yet resolved. In order to be conservative, the costs associated with new FTE hires in project management are explicitly broken out (6M\$). We assume that if all new hires are charged to the project and if all salaries have full encumbrance, then the incremental load on the "host laboratory" is effectively in the noise.

The CMS management team and the US CMS team are shown in Fig. 21. The EMU, HCAL, Trigger/DAQ, ECAL and tracking subsystems all have US coordinators/CMS project managers responsible for the costing (WBS), schedule/planning, and tracking/reporting. In FY'97 this team is augmented by a Physics Coordinator. This change is dictated by a desire, as the project becomes more mature, to insure that design choices do not compromise the physics. The tracking and reporting procedures are spelled out at length in the US CMS Project Management Plan. In subsequent subsections, the full WBS for the US CMS project, created and maintained by this team, is given.

In addition, the US CMS project team is responsible for planning/schedule. In Fig. 22 we show the overall context of CMS; the schedule for the assembly and Collision Halls, for the magnet coil and vacuum tank, and for the barrel and endcap steel flux return yoke. The magnet is, broadly speaking, the critical path item throughout the construction period of CMS.

Within this context, each US CMS project subsystem coordinator has created a consistent schedule for the subsystem. For example, in Fig. 23 is shown the schedule for the HCAL; HB, HE and HF. Clearly, HB and HE absorber structures are needed for the magnet power tests before the magnet is lowered into the Collision Hall. These, and other, connections constrain the schedule for HCAL. By attaching specific WBS items to this schedule, a technically driven spending profile is generated.

The sum of all the spending profiles resulting from this exercise is shown in Fig. 24. For comparison purposes the funding profile guidance from DOE/NSF was shown in Fig. 20. Clearly there is a mismatch, as seen in Fig. 25, where the (costs-funds) difference is shown. In order to further explore the dimensions of this apparent problem, the exercise must be refined. Note that the US CMS project leaders have attempted to delay the cost profile by spreading out spending where possible.

The DOE/NSF must explore what freedom exists to advance the US CMS funding profile within the confines of the full LHC initiative. Can the accelerator component be pushed later in time? At first glance there appears to be a profile problem, and both US CMS management, CMS management, and DOE/NSF must work together to try to find a satisfactory solution.

Figure 18: US CMS Management Responsibilities.

Figure 19: US CMS Construction Responsibilities.

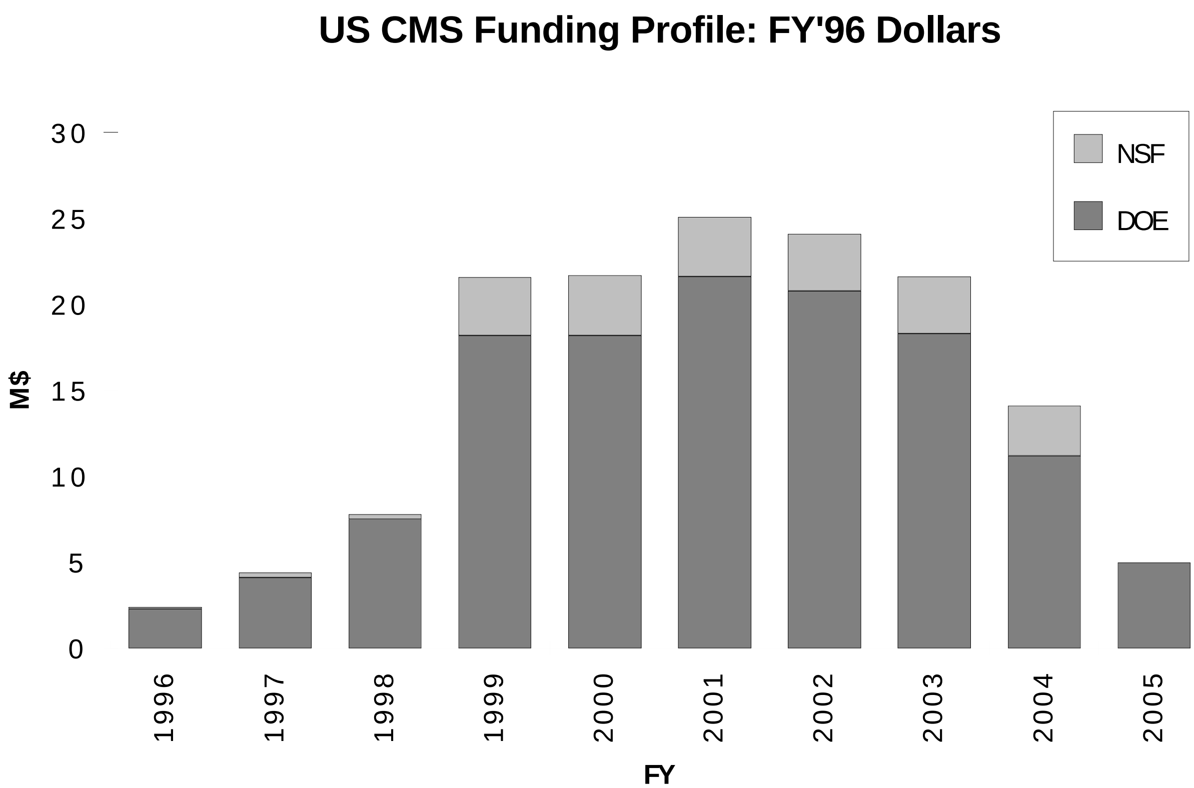
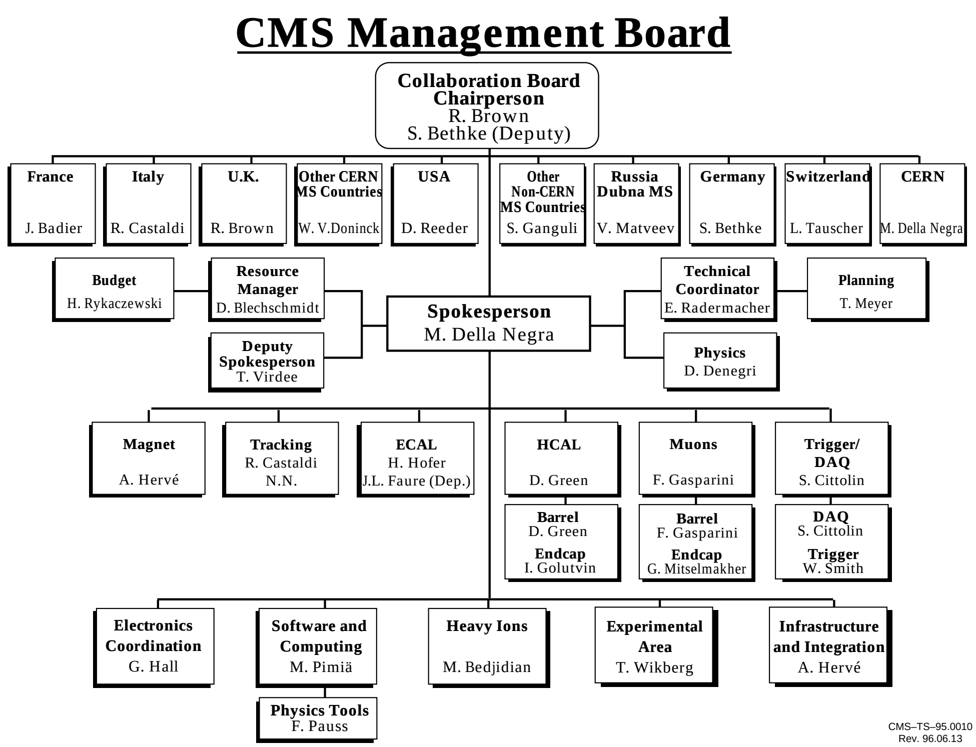


Figure 20: US CMS Funding Profile: FY'96 Dollars.



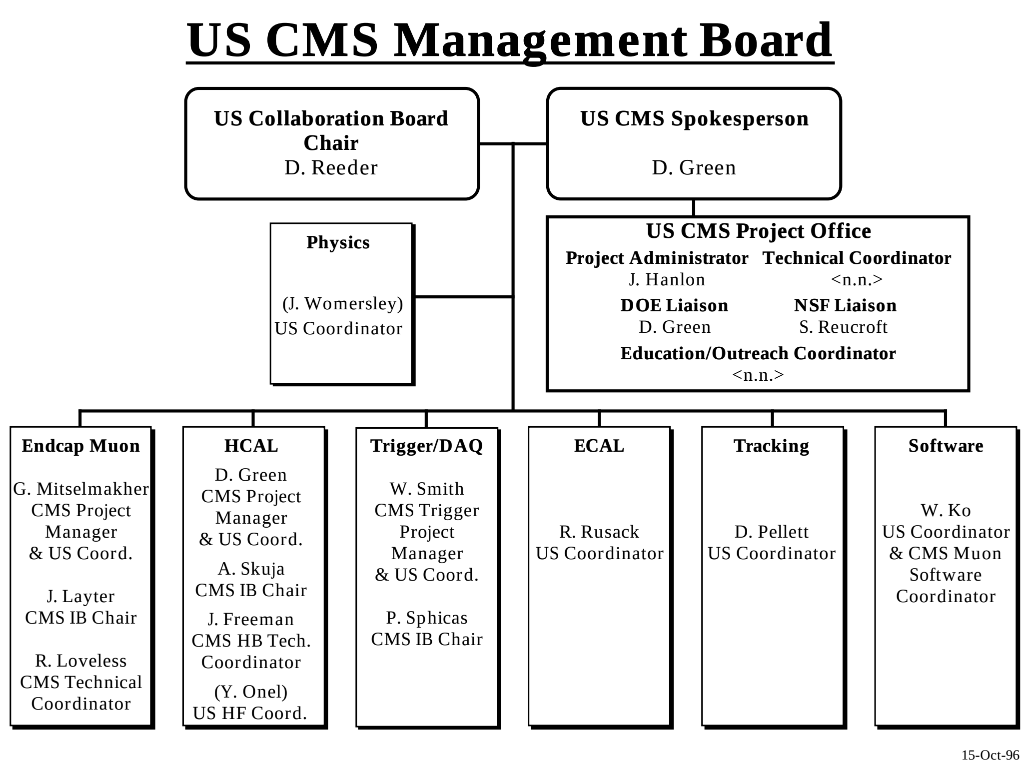


Figure 21: CMS and US CMS Management Organization.

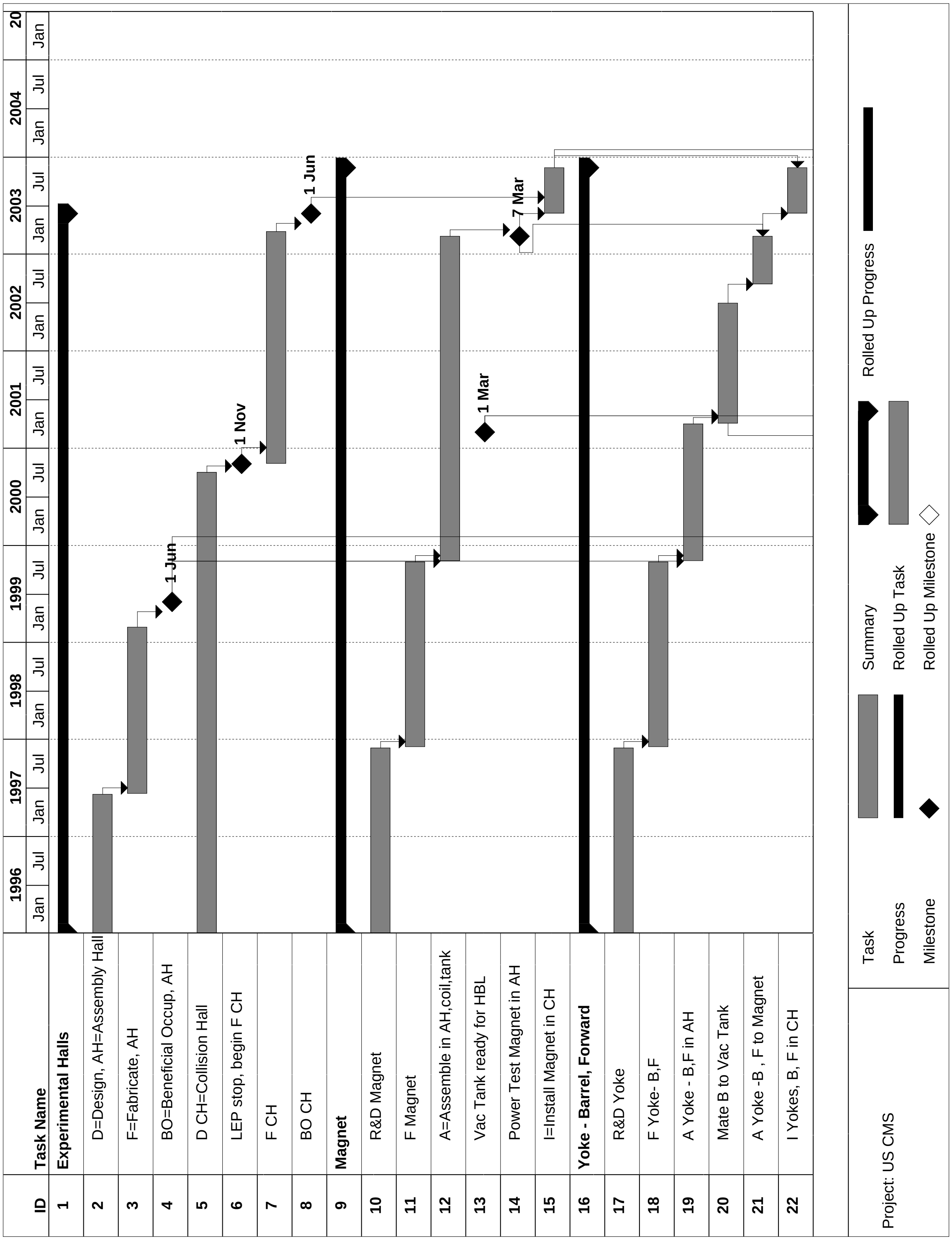


Figure 22: CMS Construction Planning.

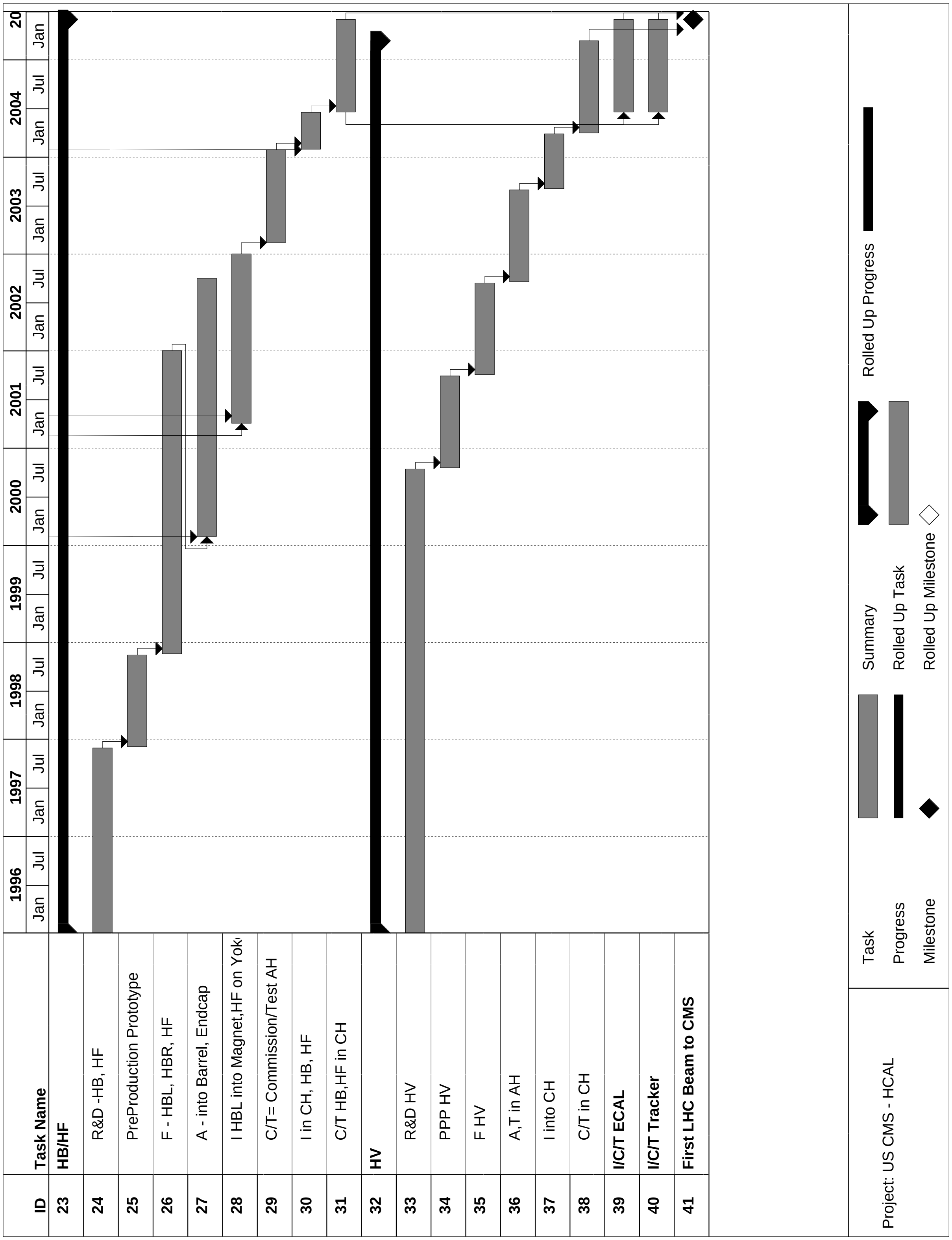


Figure 23: HCAL Construction Planning.

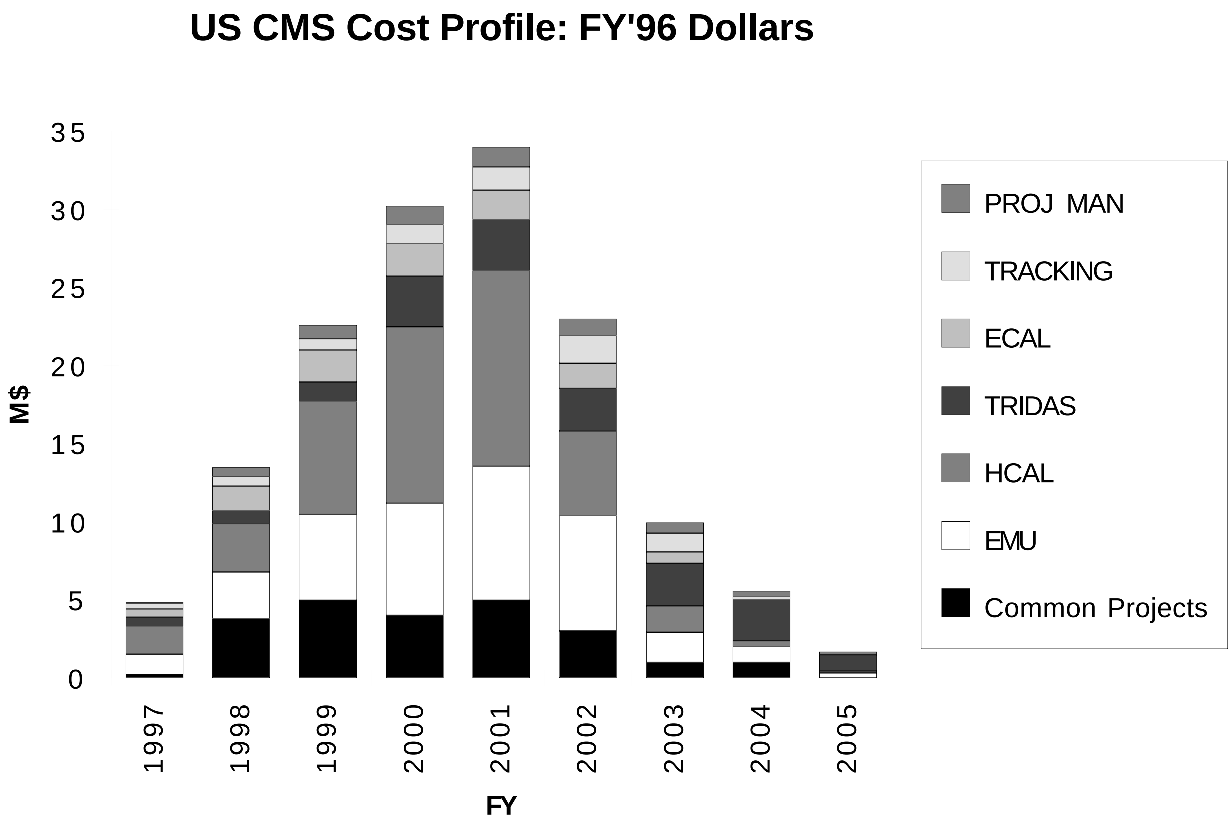


Figure 24: US CMS Costs Profile: FY'96 Dollars.

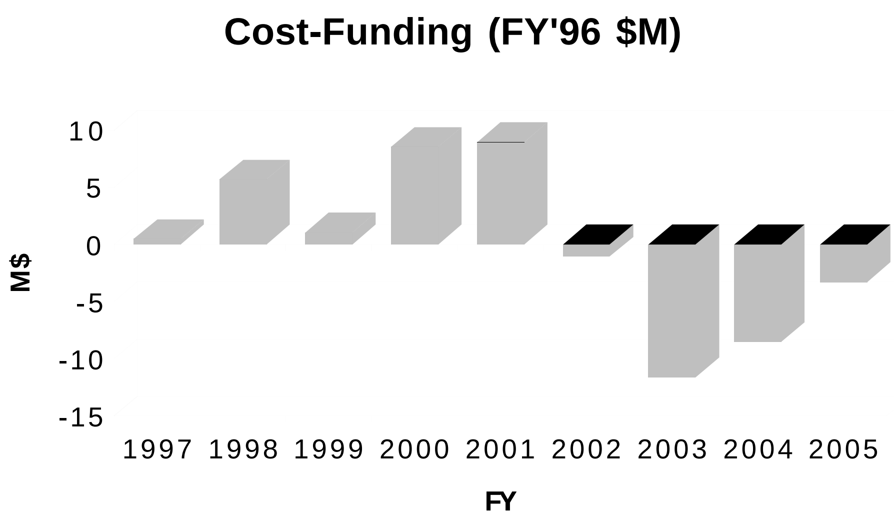


Figure 25: Cost Profile Difference: Costs - Funding.

US CMS Project Cost Estimate

15 Oct 96

WBS Number	Description	US Mfg M&S (K$)	US Mfg Labor (K$)	US EDIA (K$)	US Base Cost (K$)	US Cont (K$)	Total US Cost (K$)	DOE Request (K$)	NSF Request (K$)
US CMS Total Project Cost (then-yr $s)							**173,937**	**149,434**	**24,502**
Escalation							25,651	21,931	3,720
FY'96 R&D							2,500	2,300	200
US CMS Total Estimated Cost (FY'96 $s)		**82,890**	**12,066**	**25,025**	**119,981**	**25,805**	**145,786**	**125,204**	**20,582**
1	**Endcap Muon System**	**17,624**	**6,051**	**5,733**	**29,408**	**6,856**	**36,264**	**34,600**	**1,664**
1.1	Muon Measurement System	17,624	6,051	5,733	29,408	6,856	36,264	34,600	1,664
2	**Hadron Calorimeter**	**24,383**	**3,031**	**5,882**	**33,296**	**10,226**	**43,522**	**36,476**	**7,046**
2.1	Barrel Hadron Calorimeter	18,618	2,210	4,550	25,377	7,962	33,340	30,052	3,288
2.2	Endcap Hadron Calorimeter	3,285	530	650	4,465	1,519	5,984	2,225	3,759
2.3	Very Forward Calorimeter	2,481	291	682	3,454	745	4,199	4,199	0
3	**Trigger/Data Acquisition**	**9,957**	**464**	**3,892**	**14,313**	**4,112**	**18,425**	**16,567**	**1,858**
3.1	Endcap Muon Level 1 CSC Trigger	1,208	0	893	2,102	609	2,711	2,711	0
3.2	Calorimeter Level 1 Regional Trigger	3,089	0	1,499	4,588	1,330	5,918	5,918	0
3.3	Luminosity Monitor	345	42	48	435	87	522	0	522
3.4	Data Acquisition	5,315	422	1,452	7,189	2,085	9,274	7,937	1,336
4	**Electromagnetic Calorimeter**	**5,625**	**1,357**	**1,913**	**8,895**	**1,650**	**10,545**	**7,804**	**2,741**
4.1	Barrel Photodetectors	2,067	317	484	2,868	671	3,539	798	2,741
4.2	Front-End Electronics	2,875	445	920	4,240	722	4,962	4,962	0
4.3	Crystal Processing	166	269	358	793	77	870	870	0
4.4	Monitoring Light Source	487	321	106	914	168	1,082	1,082	0
4.5	Crystal Development	30	5	45	80	12	92	92	0
5	**Tracking**	**2,287**	**1,163**	**1,922**	**5,373**	**2,149**	**7,522**	**4,153**	**3,369**
5.1	Forward Pixel Tracker	2,287	1,163	1,922	5,373	2,149	7,522	4,153	3,369
6	**Common Projects**	**23,013**	**0**	**0**	**23,013**	**0**	**23,013**	**19,712**	**3,301**
7	**Project Management**	**0**	**0**	**5,682**	**5,682**	**813**	**6,495**	**5,892**	**602**
7.1	Project Administration	0	0	3,254	3,254	424	3,678	3,076	602
7.2	Technical Coordination	0	0	2,428	2,428	389	2,817	2,817	0

Table 19: US CMS Summary WBS.

5.1 The EMU Project

5.1.1 Endcap Muon Production Plan

This section is given in response to an action item arising from the 1995 review of US CMS.

Introduction The Endcap Muon Group needs to construct 468 Cathode Strip chambers for the CMS experiment. All these chambers are trapezoidal-shaped chambers composed of 7 honeycomb panels with 6 wire planes. There are six different size chambers, varying in size from the smallest 1.5×0.7 m^2, with roughly 400 wires per plane, to the largest 3.3×1.4 m^2, with $\sim$950 wires per plane. The group has built a number of engineering and performance prototypes (see previous sections) to develop the present design.

Description of Plan While the CSC design was evolving into the first "full-sized", 2-layer prototype (P1A) we began to develop a plan for producing the large number of CSCs for the endcap. The present plan consists of the following major operations:

- strip milling
- gluing the anode panels
- gluing the cathode panels
- winding
- soldering
- primary assembly
- final assembly
- testing and repair

Optimization During the design and prototyping steps we identified materials and labor operations which will be the major expenses of the system. We have studied these "cost-drivers" and have identified alternate materials, developed new designs, or automated assembly methods which would lower the cost and/or raise the quality and reliability of each high-cost item. The "cost drivers" we have identified are:

- **panels -** From the beginning of the project we looked for off-the-shelf honeycomb panels from vendors which could meet our requirements for flatness. All metallic honeycombs were rejected because calculations showed that the strip capacitance would be too large. We purchased many panels from a number of different vendors with plastic and paper honeycombs and tested them for flatness. The best choice was a polycarbonate honeycomb which meets our flatness requirements, the safety requirements, and was within the allowable budget.

- **strip milling -** Although original plans were to etch the cathode strips we quickly changed to the Gerber machine at Fermilab for milling when it became clear that these chambers were too large for any conventional etching vendors. We milled a number of panels on the Gerber and developed techniques which could maintain an accuracy of a few microns, without leaving any mechanical residue that could cause corona. With our encouragement Fermilab has purchased an AXXIOM machine which is a large, heavy-duty version of the Gerber and has the capability of boring holes in the panels and machining the edges as well as milling the strips. Fermilab will make this AXXIOM available to CMS for the expected 4-year production run. As a result we have agreed that **all** panels for the CSCs will be strip-milled at the Fermilab AXXIOM facility. The cost estimates for this are significantly lower than for etching all panels.

- **winding -** In standard winding technique wire is wound onto a transfer frame, glued, and transferred to a chamber frame. This is a time-consuming task which has a number of delicate steps. With the help of the Fermilab chamber winding group we developed a procedure where we can wind directly onto both sides of the actual anode panels, thus eliminating the whole transfer process. Using this procedure we wound the P1 prototype panels with our prototype winding machine. This technique eliminates a number of steps and, furthermore, enables us to remove the completed anode panel and wind another panel while the first is glued and soldered at a separate work station.

- **soldering -** As we assembled the P1A prototype (2-layer, "full-size") it quickly became clear that soldering was the single most expensive process in fabricating a CSC due to the large number of wires (and anode channels with resistors/capacitors). We surveyed a number of electronics vendors for alternatives to manually soldering all these connections. The most promising is a Panasonic system which uses a Xenon lamp focussed onto a quartz fiber optic cable with a converging lens to concentrate the energy in an intense tightly focussed spot. In a test demonstration we could solder wires in our geometry in 1.5 seconds each with very high quality. The process uses a special flux which leaves a high resistivity residue and needs no cleaning. We have purchased the major ingredients from Panasonic and are developing a computer-controlled stage with Fermilab's help. Such a system has the potential for decreasing estimated soldering costs to within the planned budget while also increasing the reliability of the connection.

We will continue search for areas where cost savings can be made. From the experience of the prototype development, we now have good cost estimates for each of the labor steps and can easily evaluate whether it would be cost-effective to develop an automatic process.

Implementation The materials and supplies will be purchased from the lowest bidders. All panels will be milled at Fermilab and possibly glued. Then panels will be shipped to primary assembly sites for the winding, soldering, and assembling. The assembled chambers will then be sent to the final assembly sites where the services and electronics are installed, and the chamber calibration, final testing, and repair (if necessary) occurs. The overall integration effort for the chambers will be handled by Wisconsin.

At this time 5 institutions have expressed an interest in becoming either a primary or final assembly site: Fermilab, Florida, UCLA, IHEP (Beijing), and PNPI (St. Petersburg). Both IHEP and PNPI are CMS collaborators and plan to contribute labor for producing CSCs as part of their contribution to CMS. The management for the endcap muon chambers remains with the US project manager; CERN has endorsed this plan. We are currently evaluating proposals from each of these sites and are developing a plan to optimize our production by leveraging the resources at each of these sites.

5.1.2 The EMU Project WBS

The WBS at level 5 for the EMU Project is shown in Table 20.

The US has full management responsibility for the endcap muon system. That system consists of Cathode Strip Chambers (CSC), Resistive Plate Chambers (RPC), front end electronics, and trigger/generation and readout electronics. Within this project, the US CMS Muon groups have construction responsibility for the bulk of the CSC and all the associated electronics.

The CSC muon measuring and triggering system consists of 4 stations of chambers, each station having 6 cathode strip and anode wire (ganged) signals for triggering and measurement. The first station has an inner and an outer set of chambers, as this is the barrel-endcap interface. The inner set is administered by the barrel management, not by the US. All the other CSC are the responsibility of the US groups.

The cathode and anode front ends, the readout electronics, and the level 1 trigger formation electronics are also part of the endcap muon project. In addition, alignment of the system is taken by US groups. This assignment is crucial, since accurate alignment is needed if an incisive trigger Pt edge is to be achieved.

Of course tooling and fixturing for detector installation is part of the Project, as are the necessary services, gas, low voltage, high voltage, cooling, and slow controls.

5.2 The Hadron Calorimeter Project

The US groups in CMS have full Project Management responsibility within CMS for the Hadron Calorimeter (HCAL). This fact is reflected in the CMS organization chart for HCAL which has already been shown. The US has construction responsibility for a limited subset of the HCAL. We are responsible for the barrel absorber structure, the active scintillator samples, the transducers, the front end electronics, the readout and the trigger primitives. Basically the US groups buy and build everything in the HCAL barrel from mechanics to triggers.

Outside the barrel there are 2 samples for late developing showers. The scintillator is the responsibility of the Indian groups, while the transducer and everything "downstream" are US responsibilities. In the endcap a similar situation obtains. Russian/Dubna Member States (RDMS) groups are largely responsible for the absorber and the scintillator. The US groups build the optical fibers to the transducers and everything "downstream". For the forward calorimeter, HF, the absorber and sampling active elements are purchased and built by groups from Russia, Italy, Hungary and Turkey. The US groups are responsible for some of the quartz fiber readout, the transducers and all "downstream" elements. Therefore, there is an economy of scale for the US, in that, for all calorimeter segments, we cover the transducers and electronics.

A summary for HCAL to level 5 in the WBS is given in Table 21. The full project is shown, since US groups have project management responsibility for HCAL. However, only US costs are shown, while contributions from India, Russia/Dubna Member States, China, Hungary, and Turkey are shown at zero cost to the US. As an example of the level of detail available, we show in Table 22 the first page of a level 7 HCAL WBS indicating unit costs and labor operations.

5.3 Trigger/Data Acquisition Project

The US groups in CMS have full Project Management responsibility within CMS for the Trigger. They also have responsibility for the Event Builder, Higher Level Trigger, and Luminosity Monitor subprojects. This fact is reflected in the CMS organization chart for Trigger and Data Acquisition (TRIDAS) which has already been shown. The US has full construction responsibility for a limited subset of the TRIDAS project, including the calorimeter trigger level 1 regional processing, the endcap muon CSC level 1 trigger, and the luminosity monitor. The US has partial construction responsibility for a subset of the data acquisition system including the readout dual port memories, the readout data links, the readout crate supervisor, the readout flow controller, the event builder and the filter farm interface.

The regional processing system of the calorimeter level 1 trigger processes the electromagnetic and hadronic trigger tower sums from the calorimeter front end electronics and delivers regional information on electrons, photons, jets, and partial energy sums to the global calorimeter level 1 trigger system. The system begins after the data from the front end electronics is received on optical fibers and translated to signals on copper and ends with cables that transmit the results to the calorimeter global level 1 trigger system.

The trigger electronics for the endcap CSC muon system finds muon track segments in each chamber and links them together to determine momentum and reduce background rates. The 25ns muon bunch crossing is determined for each muon segment. Because of the limited bending power in the forward region, the muon trigger is designed for very high precision in the bend coordinate. Because of huge background rates from punchthrough, decays in flight, and low-momentum prompt muons, the trigger is designed to take maximum advantage of the highly redundant CSC chamber system.

The determination of the proton-proton luminosity in the CMS interaction region is an essential ingredient in the measurement of all absolute cross sections. The scope of the luminosity subgroup includes the following topics: absolute luminosity measurements; relative luminosity measurements over time; monitoring of beam-gas backgrounds and backgrounds during beam tuning and scraping; development of detectors for luminosity and background monitoring; physics topics associated with detectors used for luminosity monitoring; luminosity information exchange between CMS and the LHC machine.

The event-building and High-Level Trigger subsystems are responsible for transporting the data upstream and providing an extra rejection factor of 1000 against backgrounds at design luminosity. After a Level-1 trigger accept, an event is read into approximately 1000 independent memories. These buffers are sent to a single intelligence (a processor) for further analysis. The connection between the buffers and processors is achieved via a switch. The collection of switch inputs (the Readout Dual Ported Memories), switch outputs (Filter Farm Interface) and the switch itself comprise the event building network. This system is controlled by the Event Manager which is responsible for synchronizing inputs and outputs.

The Trigger/Data Acquisition WBS is given in Table 23.

5.4 The Electromagnetic Calorimeter Project

The US groups in CMS have well defined construction responsibilities for the ECAL. The US effort falls into 3 major and critical areas. First, based on the extensive L3 experience of the Princeton group, the US is responsible for the design and construction of the ECAL very front end electronics. As this is the most precise calorimetric device in CMS, requiring low noise, a large dynamic range, high speed, and radiation resistance, this electronics is very challenging.

Second, the transducer for ECAL has been chosen to be an Avalanche Photodiode (APD). Based on their SSC experience, US groups – NEU and Minnesota – are leading the development work on the APD done in collaboration with US industry. They will later take responsibility for procurement and testing of a large fraction of the ECAL APD.

Third, there is considerable expertise in the US on crystal characterization and preparation from L3 and BaBar experience at Caltech and LLNL. These groups will develop the crystal surface finishing techniques for the $PbWO_4$ crystals, using their unique capabilities. They will also plan, develop, and build the calibration and monitoring system which is needed to track the ECAL and thus preserve its energy measuring accuracy.

The WBS to level 5 for ECAL is given in Table 24.

5.5 The Pixel Tracker Project

The CMS Tracking system consists of silicon pixels, silicon strips and MicroStrip Gas Chambers (MSGC). The addition of pixels in CMS was influenced by a proposal by US groups to enhance the B tagging and heavy flavor capabilities of CMS by making that addition.

Thus, it is very natural for US groups to take responsibility for all the endcap pixel detectors in CMS, since the pixels in CMS are due in part to an initiative by US groups based on expertise developed in the US Pixel R&D Program in the SSC era. They also bring significant expertise from their CDF, D0 and L3 experiences.

The design of the readout to meet LHC specifications is a critical task for the pixel system. UC Davis leads this development work in the US, along with the bonding to the detectors themselves. Purdue will take the lead in acceptance testing of readout arrays.

The devices themselves must be characterized and their ability to withstand the harsh LHC radiation environment must be established. The Johns Hopkins group has major responsibility in this area. Testing is thought to be done mostly at the Fermilab Booster where a test setup for CDF/D0 is being set up. Johns Hopkins is also responsible for the signal handling between the pixel readout and the rest of the DAQ system.

The mechanical design of the pixel support wheels and cooling system, their assembly, pixel array mounting and alignment, and the subsequent cooling and survey are US responsibilities. Northwestern and Mississippi with Fermilab lead the mechanical and cooling design and Fermilab the assembly, alignment and testing program, with participation by Texas Tech.

The design must pass muster for impact parameter resolution, pattern recognition and secondary vertex reconstruction. The Florida State (SCRI) and Rice groups are heavily involved in these efforts. Johns Hopkins and UC Davis also have important roles in the pixel simulation. In sum, the US CMS groups have the full and complete responsibility to deliver working wheels of endcap pixel detectors.

The pixel WBS is given in Table 25.

Table 20: EMU Cost Estimate

Table 21: HCAL Cost Estimate

Table 22: HCAL WBS Detail.

US HCAL Cost Estimate: (FY'96 US $) 15 Oct 96

WBS Number	Description	Unit	Unit Cost ($)	Quantity	Mfg M&S (K$)	Mfg Labor (Yrs)	Mfg Labor (K$)	EDIA Labor (K$)
2	**Hadron Calorimeter**				**35,717**	**98**	**4,069**	**7,400**
2.1	**Barrel Hadron Calorimeter (HB)**				**20,345**	**63**	**2,606**	**5,050**
2.1.1	Barrel				17,401	50	2,053	4,300
2.1.1.1	Mechanical Structure				8,401		0	1,100
2.1.1.1.1	*Barrel Design*							*1,100*
2.1.1.1.2	***Barrel Wedges***			***36***	***6,241***			
	Copper plates	*lb*	*2.5*	*69342*	*6,241*			
2.1.1.1.3	*Bolted Assembly*	*Wedge*	*60000*	*36*	*2,160*			
2.1.1.2	Optical System				1,663	18.4	784	800
2.1.1.2.1	***Tile Trays (20 degree)***			***594***	***1,337***	***6.6***	***298***	***300***
	Tile Tray Design							*300*
	Scint. plate (4mm SCSN81, +40%)	*sqm*	*303*	*5.6*	*1,008*			
	Megatile machining (2/day; 1 tech)	*ts hrs*	*29.03*	*3.7*		*1.1*	*64*	
	MTile fab epoxy (2/day w 2 techs)	*tc hrs*	*20.64*	*1.5*		*0.4*	*18*	
	MTile fab (paint)	*tc hrs*	*20.64*	*0.3*		*0.1*	*4*	
	MTile fabrication inspect,store	*tc hrs*	*20.64*	*2*		*0.6*	*25*	
	Plastic cover material (30% over)	*sqm*	*50*	*1.4*	*42*			
	Plastic cover machining	*ts hrs*	*29.03*	*1.3*		*0.4*	*22*	
	Aluminum cover, top	*each*	*35*	*1*	*21*			
	Aluminum cover, bottom	*each*	*10*	*1*	*6*			
	Shoulder pins (rivets)	*each*	*0.2*	*15*	*2*			
	Assemble tiles into pans	*tc hrs*	*20.64*	*2*		*0.6*	*25*	
	Wrapping material	*sqm*	*5*	*1*	*3*			
	Wrapping material, punch	*tc hrs*	*20.64*	*1*		*0.3*	*12*	
	Align pans and pins	*tc hrs*	*20.64*	*2*		*0.6*	*25*	
	tape pan edges	*tc hrs*	*20.64*	*0.5*		*0.1*	*6*	
	test pans, 2/day	*tc hrs*	*20.64*	*4*		*1.2*	*49*	
	packing material and crate, 10/crate	*each*	*2000*	*0.1*	*119*			
	Disposables per pizza pan	*each*	*200*	*1*	*119*			
	Source tubes	*m*	*0.6*	*20*	*7*			
	Source tube funnel	*each*	*0.25*	*4*	*1*			
	Source tube install	*tc hrs*	*20.64*	*4*		*1.2*	*49*	
	Pan capture fixture	*each*	*0.2*	*4*	*0*			
	Installation disposables	*each*	*16.84*	*1*	*10*			
2.1.1.2.2	***Optical Cables***			***2376***	***113***	***1.8***	***76***	***150***
	Optical cables EDIA							*150*
	Optical connectors (dbl end cables)	*each*	*5*	*2*	*24*			
	Acrylic multi-fiber cable (17 fibers	*m*	*15*	*2.5*	*89*			
	Assembly (cement and polish)	*tc hrs*	*20.64*	*1.3*		*1.5*	*64*	
	Test	*tc hrs*	*20.64*	*0.25*		*0.3*	*12*	
2.1.1.2.3	***Pig Tails***			***2376***	***203***	***8.1***	***335***	***200***
	Pig tails design							*200*
	*WLS fiber(17*1.2m)*1.3*	*m*	*1*	*26.52*	*63*			
	*Clear fiber (17*2.4m)*1.3*	*m*	*1*	*48.96*	*116*			
	WLS fibers, cut & polish (20/hr +20%	*tc hrs*	*20.64*	*1.7*		*2.0*	*83*	

Table 23: Trigger/DAQ Cost Estimate

Table 24: ECAL Cost Estimate

Table 25: Tracking WBS

6 NSF Supported Projects

6.1 Introduction

The complete account of the role of the NSF groups in CMS (both R&D and CMS project activities) within US CMS is contained in the two proposals to the NSF [2]. These documents contain a description of the work done in FY'96 by NSF supported groups on R&D for US CMS, a discussion of the proposed efforts in FY'97, FY'98, and FY'99, and an exposition of the role of the eight NSF supported groups in US CMS with respect to their responsibilities in the US CMS Project.

Therefore, in this section we simply summarize the budgets implied by the milestones and schedules pertaining to the efforts of NSF supported groups within US CMS plus we give a brief discussion of our plans to exploit the educational aspects of CMS in bringing the excitement of the project to a wide audience. Note that for DOE supported groups we have exact guidance as to the level of support. For NSF supported groups we have documented the cost profile implied by the CMS schedule rather than the funding profile. For the NSF groups the ratio of cost profile to funding profile is about two for FY'97.

In general, as discussed in Section 5, a first attempt to work out a cost profile for the US CMS Project shows that there is a mismatch between the funding profile guidance given by NSF and DOE and the cost profile which has resulted from the bottoms up WBS exercise just completed and the profile implied by performing the schedule exercise described in Section 5. In the case of DOE supported groups, we have simply worked within the guidance given to us in FY'97 and noted, in Section 3, where we fall short of the CMS schedule and milestones. For subsequent years, the disparity between cost and funding profiles is explained in Section 5. In the case of NSF supported groups we have shown the guidance funding profile in Section 5. However, for costs in FY'97 we have indicated real needs. That disparity is a factor 2.5 for FY'97, $782K vs. $300K. Thus, the treatment of NSF groups is indicative of the changes which would be needed in the funding profile of all groups in order that the US CMS Project schedule be achieved in FY'98 and beyond.

6.2 Education Integration Issues

The CMS-NSF groups will continue to include a strong educational component as part of their research program. No funding for this is being sought in either of the two CMS-NSF proposals. Other proposals either already have been, or will be submitted.

One of the most important posts in the US CMS Project Office based at Fermilab is that of Education Coordinator. We have just launched a search process to fill this post. Statements of interest and qualification are being sought from members of US CMS who have a particular interest in bringing the techniques and physics of CMS to as wide an audience as possible. Responsibilities of the Education Coordinator will include coordinating the ongoing education and outreach activities of all groups and seeking new and innovative ways of involving the whole community in CMS.

Some examples of our ongoing activities are listed below. The Education Coordinator will help us decide which, if any, of these are most likely to assist us in reaching-out and introducing the excitement and importance of the highest energy particle physics to non-experts. Also appearing in the US CMS Project Office is Marge Bardeen, who serves as US CMS liaison to the Fermilab Education Office.

World Wide Web
The World Wide Web was developed at CERN and is heavily used within CMS to facilitate the communication of information between distributed collaborators. It is also an ideal medium for presenting HEP to the general public, and in particular to secondary schools and undergraduate physics departments throughout the US. We are already studying the use of Java to provide interactive educational tools on the Web, one example being a simplified version of the CMS event display program.

MInDLab
We also have a proposal under consideration by the DOE SBIR program for a Mobile Interactive Detector Laboratory (MInDLab). The proposal was submitted by a small company based in North Carolina (Quantum Research Services, Inc.) and involves several CMS physicists as consultants. MInDLab would bring sophisticated interactive experiments to schools lacking such facilities. Interactive examples of CMS techniques and physics goals, as demonstrations of a state-of-the-art experiment, would be included.

Joint Education-Physics Program
Education programs have felt an increasing pressure to include not only pedagogical studies, but also to have their participants be experts in some particular field. We are in the process of submitting a proposal for a joint program that would include work on CMS as part of a physics-education degree for high-school teacher training.

Fermilab Education Program The Fermilab commitment to enhancing mathematics and science education and stimulating science literacy has four major objectives: strengthening mathematics and science education throughout the system, especially in the early years; increasing the number of teachers with a substantive background in science and mathematics via e.g. staff development opportunities; increasing the number of young students, especially girls and members of minorities, who retain their curiosity about the natural world as they grow up; increasing the number of undergraduate and graduate students, especially women and members of minorities, who complete degrees in science, particularly particle physics, mathematics and technology. For more details, see the Fermilab Education web site [34].

Physics Undergraduate Students/ Co-op Students
Most CMS-NSF groups also include undergraduate students in their research programs, and this is anticipated to continue in CMS. In particular, the Northeastern group gives out undergraduate co-op positions for students to spend one or more quarters at a lab, normally either Fermilab or CERN. Although not primarily intended as a feeder program for graduate schools, a number of Northeastern co-ops have gone on to study physics at other prestigious schools. Notre Dame has maintained an NSF/REU summer program for college juniors which has been in place for better part of a decade. Each year the Notre Dame group has had the active and effective participation of these students in several experiments at

Fermilab. Beginning in Summer, 1996 this will also involve CMS.

Science Alive The Notre Dame group has participated in "Science Alive", an outreach program in the South Bend community, to interest primary and secondary school children in science, physics, and high energy physics. Similar programs are being developed by other groups.

Physics Graduate Students
Of course, we will continue to educate the traditional Ph.D.-bound student in research techniques and procedures. Eventually students will receive their Ph.D.'s on CMS data, but due to the long construction period, the early years will be used to give hands-on design and construction experience to students who otherwise could spend their entire graduate careers doing only analysis. This is also true for MS students who take the thesis option.

6.3 Project Budget

6.3.1 Construction Summary

In this section, we present a summary of the cost of the construction for the NSF projects described above. This summary has been extracted from the overall cost estimates of the US portion of the CMS project as produced by the US CMS Management Board. In fact, since the Management Board has the ultimate responsibility for the assignment of monies to tasks it is not unlikely that the amounts in the table will be subject to fine-tuning before distribution to individual projects. This distribution will be administered via sub-contracts to the appropriate university groups. The larger context for this proposal and these construction costs is contained in the CMS Technical Proposal (CERN/LHCC 94-38) and in the US CMS Letter of Intent of September 1995 and the governance aspects are covered in the US CMS Project Management Plan.

The eight-year budget request covers construction and R&D work for the following subsystems: Endcap Muon (EMU), Hadron Calorimeter (HCAL), Trigger/DAQ, Electromagnetic Calorimeter (ECAL), Tracking, and Computing/Software (although, as can be seen from the table below, no funds are being requested for Computing and Software work). Work related to the luminosity monitor is included in the Trigger/DAQ subsystem. Monies will be used for equipment and materials, travel and necessary short-term engineering and technical support. No monies will be used to pay the salaries of research personnel. Note that FY'97, FY'98 and FY'99 R&D expenditures are included in the corresponding project funding requests. On the other hand, the FY'96 R&D award is not included.

Construction Budget Summary by Project. (All amounts in FY'97 $M).

Project	Request
Endcap Muon Alignment	1.711
Hadron Calorimeter Readout	7.243
Trigger/DAQ	1.910
(Luminosity Monitor)	0.537
Electromagnetic Calorimeter Readout	2.819
Pixel Tracking System	3.463
Computing and Software	0.0
Common	3.393
Total Request	20.539

A more detailed summary of the costs per subsystem is contained in the attached WBS which outlines the costs of the US CMS project in FY'96 dollars. The specific NSF subset of the project is projected out in the second summary table. In order to convert FY'96 dollars to FY'97 dollars, one multiplies by 1.028.

6.3.2 Cost Profile of the Total Project

The table below shows the costs for the years between FY'96 and FY'05, inclusive. Details may change as experience is gained with different aspects of the project; this table gives the cost profile as presented to US CMS by the NSF and modified to accommodate adequate R&D funds for the first four years. Details of the R&D funding are given in the companion proposal "CMS Detector R&D". All amounts in this table are given in FY'97 dollars.

Preliminary US CMS Cost Profile. (All amounts in FY'97 $M).

Fiscal Year	FY96	FY97	FY98	FY99	FY00	FY01	FY02	FY03	FY04	FY05	Total
NSF R&D	0.2	0.59	0.63	0.61							2.03
NSF Project				2.9	3.4	3.3	3.2	3.2	2.7		18.7
Total	0.2	0.59	0.63	3.51	3.4	3.3	3.2	3.2	2.7		20.74

6.3.3 Description of NSF-1030 Budget Forms

All budget items are given in FY'97 dollars. The already awarded FY'96 R&D amount of $200000 is not included.

The project proper is totally contained in the 9 sub-contracts of line G.5, an eight-year total of $20539000. The only other direct cost is the salary plus fringe benefit (at 28.9%) for an administrative assistant. At $30000 *per annum*, this yields an eight-year total of $240000 with associated fringe benefit costs of $69360. An administrative assistant is needed to administer the sub-contracts and to work closely with the Project Management Office at FNAL to ensure accurate accounting and tracking of NSF funds and to help provide timely status reports.

Indirect costs are calculated using the on-campus rate of 58% applied to an overhead base of $25000 per sub-contract plus the administrative assistant salary and fringe benefit; the overhead base is therefore $225000 plus $309360.

6.3.4 NSF WBS

The US CMS WBS, given in Section 5, was computed in FY'96 dollars. In Table 26 we show the elements of that WBS for which NSF is responsible. The total is in FY'96 dollars is 20,582 K$, or in FY'97 dollars 21,159 K$. At WBS level 6 or lower individual items are labeled as NSF or DOE items, as can be seen in the level 7 HCAL WBS example page shown in Section 5.

6.4 R&D Budget

The larger context for this proposal and these R&D costs is contained in the CMS Technical Proposal (CERN/LHCC 94-38), in the US CMS Letter of Intent of September 1995 and in the companion NSF proposal "CMS Construction Project". The governance aspects are covered in the US CMS Project Management Plan. It is perhaps important to point out here that whenever funds for "travel" are mentioned in the following, these refer to the necessary travel items for non-physicist personnel such as engineers, technicians, etc. These funds are part of the EDIA entry in the corresponding WBS line given in the aforementioned companion NSF proposal.

6.4.1 R&D Budget Summary by Year

This section gives some details of the plans of each group for R&D in fiscal years 1997, 1998 and 1999. In addition, we note the FY'96 activities that have already been completed.

The total amount for FY'96 was \$200K, which was awarded in subcontracts according to the following table.

Group	Awarded Amount (FY96)
UCLA	\$5K
UC San Diego	\$10K
U Illinois (Chicago)	\$25K
Johns Hopkins	\$25K
U Nebraska (Lincoln)	\$25K
Northeastern - ECAL	\$25K
Northeastern - EMU	\$25K
U Notre Dame	\$25K
Virginia Tech	\$25K
Northeastern - Overhead	\$10K
Total	\$200K

The FY'97, FY'98 and FY'99 amounts are summarized by group and by subsystem project in the corresponding tables, and the overall budget for all R&D is presented on the attached NSF-1030 budget forms. Individual group NSF-1030 budget forms will be prepared when final awarded amounts are known.

FY'96

This year has been essentially one of preliminary studies, and preparation for funded research in FY'97. The EMU group (Northeastern) has been investigating possible sensors and fixtures for the alignment system. The HCAL groups (UIC, Notre Dame, and VPI) have spent their time studying various connector and lightguide options in preparation for FY'97, as well as investigating various options for providing high voltage to the HPMT tubes.

The Trigger/DAQ groups (UCSD and UCLA) have been working on feasibility studies for various designs, and early studies of luminosity monitor designs were carried out by the groups involved (U. Nebraska and UCLA). The ECAL group (Northeastern University) has continued work on ECAL R&D, characterizing APD's and studying their radiation hardness, as well as the radiation hardness of related devices such as temperature sensors. It was discovered in the course of these irradiations that some temperature sensing devices fail after neutron exposures expected after only a short period of CMS running. The group also participated in ECAL test beams, studying various crystal and readout possibilities. The tracking group (Johns Hopkins) did preliminary pixel studies in FY'96.

Computing work, though of paramount importance, especially in the design phases of an experiment like CMS, is funded through the base budgets of the groups involved. Major contributions have been made by the Johns Hopkins group and, in particular, by the Northeastern group which has been responsible for a large part of the standard CMS simulation and visualization code.

FY'97

The EMU group will spend the bulk of the time investigating prototypes for the sensors and fixtures for which \$20K is anticipated, with \$26K for a technician, \$24K for equipment and instrumentation and \$13K for travel.

The HCAL group expects to complete pigtail tester development during this year, and to continue working on fiber studies and scintillator R&D. UND and UIC request \$46K and \$29K respectively for personnel, \$10K each for travel. UIC expects to spend \$26K for materials and construction with UND spending \$30K plus another \$20K of university matching funds. The VPI group plans to begin procurement of HPMT's, purchasing \$20K worth of the devices in this year and anticipating \$35K for engineering, design and supplies and \$5K for travel.

The Trigger/DAQ group will spend \$44K on engineering of the RDL and in particular of the ATM links, with \$12K anticipated for travel. The Luminosity group will construct a cosmic ray test stand for \$9.5K, counter prototypes for \$3.65K and to accomplish these tasks spend \$18.3K in salaries of part-time help. About \$8K is anticipated for travel.

The ECAL group will continue work on ECAL R&D, characterizing APD's and studying their radiation hardness, as well as the radiation hardness of related devices such as temperature sensors. Definitive studies at ORNL are planned, as well as continuing device development studies with manufacturers. Tests of new devices with reduced noise and nuclear counter effects are anticipated, as well studies of alternative passivation schemes and their influence on radiation hardness. The group will also participate in ECAL test beams, studying various crystal and readout possibilities. For these tasks, \$57K is requested to purchase devices, and pay for temporary technical and engineering work, and corresponding travel.

The tracking group requests \$130K for their pixel development work. This is expected to be the first year of a uniform development project over three years involving design and fabrication of the detector array for \$83K (including probe tests, beam and radiation tests), the local comm. chips for \$33K, kapton cables for \$8K, and the optical transmitter for \$6K.

FY'98

The EMU group will continue to spend the bulk of the time investigating the sensors and fixtures for which \$24K is anticipated, with \$26K for a technician and \$15K for travel.

The HCAL group will finish fiber studies, and intensify scintillator R&D with the aim of completing both during this year. Mixer box development is expected to be well advanced at this stage. UIC and UND request \$29K and \$47K respectively for personnel, and \$10K and \$15K for travel. UIC will spend \$22K for materials and construction and \$6K for test beam work. UND, having completed the pigtail tester R&D expects to continue fiber studies for \$3K, and spend \$20K on intensified scintillator R&D. Lightguide and mixer box work is expected to continue with \$20K provided as university matching funds. The VPI group plans to begin procurement of HPMT's, purchasing \$20 K worth of the devices in this year, and anticipating \$35K for engineering, design, and supplies, and \$5K for travel.

The Trigger/DAQ group will spend \$40K on engineering, with \$12K anticipated for travel, and \$40K for development systems and prototypes. The Luminosity group will purchase prototype phototubes and electronics for \$16K, and spend some \$21.8K in salaries. About \$13K is anticipated for travel.

The ECAL group will continue work on ECAL R& D, characterizing APD's and studying their radiation hardness, as well as the radiation hardness of related devices. Test beam work is expected to continue with increasing emphasis on the overall ECAL design including realistic crystal arrays and readout electronics. \$52K is requested to continue this work, and in particular to pay for devices, and technical and engineering work.

The tracking group requests \$140K to continue the 3-year pixel development work, including fabrication and testing with increased emphasis on the detector array and kapton cable development.

FY'99

The EMU group will continue to investigate the sensors and associated fixtures for which \$6K is anticipated, with \$26K for a technician and \$15K for travel.

The HCAL group plans to intensify and conclude R&D for the mixer box and for the connectors and lightguides. UIC anticipates \$45K for technicians, \$10K for travel, and \$17K for production of light guides. UND requests \$49K for salaries, \$15K for travel, and \$20K (plus \$20K of university matching funds) to finish the mixer box and connector/light guide work. The VPI group plans to begin procurement of HPMT's, purchasing \$20 K worth of the devices in this year, and anticipating \$35K for engineering, design, and supplies, and \$5K for travel.

The Trigger/DAQ group will spend \$40K on engineering, with \$12K anticipated for travel, and \$40K for development systems and prototypes. The Luminosity subgroup will continue prototype studies for the forward proton detectors, spending \$8K on prototype equipment. They request \$24.9K in salaries. About \$9K is anticipated for travel.

The ECAL group will continue work on ECAL R&D, characterizing APD's and developing techniques to handle the large-scale device characterization required for the construction phase. They expect to continue to participate in ECAL test beams, with increasingly realistic setups and improved crystals and APD's. A request of \$46K is made to cover device procurement and equipment expenses, and to pay for two temporary technicians.

The tracking group requests \$150K to conclude the pixel development work, including fabrication and testing. In this final year of development, while all facets of the work continue, emphasis will be on final fabrication of the detector array and local comm. chips.

6.4.2 R&D Budget Summary by Project

In this section, we present the proposed R&D budget divided up by subsystem. The detailed distribution of monies to the eight groups is given in the next section. The nominal budgeted amounts per R&D activity are shown in the table below. The US CMS Management Board has the ultimate responsibility for the detailed allocation of monies to tasks and it is possible that the amounts in the table will be subject to fine-tuning before distribution to individual groups. This distribution will be administered via sub-contracts to the appropriate university groups.

The three-year budget request covers R&D work for the following subsystems: Endcap Muon (EMU), Hadron Calorimeter (HCAL), Trigger/DAQ, Electromagnetic Calorimeter (ECAL), Tracking and Computing/Software (although in actual fact no funds are being requested for the Computing and Software work). Work related to the Luminosity Monitor is included in the Trigger/DAQ subsystem. Monies will be used for equipment and materials, travel and necessary short-term engineering and technical support. No monies will be used to pay the salaries of research personnel.

R&D Budget Summary by Subsystem. (All amounts in FY'97 $K).

Subsystem	FY97 Request	FY98 Request	FY99 Request	Total R&D Request
EMU	83	65	47	195
HCAL	211	212	216	639
Trigger/DAQ	109	161	151	421
ECAL	57	52	46	155
Tracking	130	140	150	420
Computing/Software	0	0	0	0
Total	590	630	610	1830

6.4.3 R&D Budget Summary by Group

The requested amounts according to university group are shown in the following table. As noted above, these amounts may change slightly after consultation with the Management Board, although the total will not.

R&D Budget Summary by Group. (All amounts in FY'97 $K).

Group	Subsystem	Contact	FY97	FY98	FY99	Total R&D
UCLA	Trigger/DAQ	Schlein	6	46	46	98
UC San Diego	DAQ	Paar	50	46	46	142
U Illinois	HCAL Readout	Adams	65	67	72	204
Johns Hopkins	Forward Pixel Tracking	Chien	130	140	150	420
U Nebraska	Luminosity Monitor	Snow	53	69	59	181
Northeastern	ECAL Readout	Reucroft	57	52	46	155
	Endcap Muon Alignment	Moromisato	83	65	47	195
	Computing/Software	Taylor	0	0	0	0
U Notre Dame	HCAL Readout	Ruchti	86	85	84	255
Virginia Tech	HCAL Readout	Mo	60	60	60	180
Total			590	630	610	1830

6.4.4 Description of NSF-1030 Budget Forms

All budget items are given in FY'97 dollars. The already awarded FY'96 R&D amount of $200K is not included.

Funding for the R&D of the eight university groups is contained in the 9 sub-contracts of line G.5, a three-year total of $1830000. The only other direct cost is the salary plus fringe benefit (at 28.9%) for an administrative assistant. At $30000 *per annum*, this yields a three-year total of $90000 with associated fringe benefit costs of $26010. An administrative assistant is needed to administer the sub-contracts and to work closely with the Project Management Office at FNAL to ensure accurate accounting and tracking of NSF funds and to help provide timely status reports.

Indirect costs are calculated using the on-campus rate of 58% applied to an overhead base of $25000 per sub-contract plus the administrative assistant salary and fringe benefit; the overhead base is therefore $225000 plus $116010.

Table 26: NSF WBS.

US CMS NSF Cost Estimate

15 Oct 96 (1 of 3)

WBS Number	Description	US Mfg M&S (K$)	US Mfg Labor (K$)	US EDIA (K$)	US Base Cost (K$)	US Cont (K$)	Total US Cost (K$)	NSF Request (K$)
plus FY'96 R&D							200	200
US CMS Total NSF Est. Cost (FY'97 $s)		**12,084**	**1,516**	**3,473**	**17,073**	**4,086**	**21,159**	**21,159**
US CMS Total NSF Est. Cost (FY'96 $s)		**11,755**	**1,474**	**3,378**	**16,608**	**3,975**	**20,582**	**20,582**
1	**Endcap Muon System**	**781**	**194**	**368**	**1,343**	**321**	**1,664**	**1,664**
1.1	**Muon Measurement System**	**781**	**194**	**368**	**1,343**	**321**	**1,664**	**1,664**
1.1.1	CSC Chambers	67	74	730	144	35	179	179
1.1.1.7	MF2/2, MF3/2, MF4/2	67	74	3	144	35	179	179
1.1.7	Alignment	714	120	365	1,199	286	1,485	1,485
1.1.7.1	Global linking	133		70	203	48	251	251
1.1.7.2	CSC layer monitor	476		235	711	170	881	881
1.1.7.3	Endcap alignment	100		30	130	31	161	161
1.1.7.4	Accelerator linking	5		30	35	8	43	43
1.1.7.5	Installation		120	0	120	29	149	149
2	**Hadron Calorimeter**	**3,410**	**704**	**1,164**	**5,278**	**1,769**	**7,046**	**7,046**
2.1	**Barrel Hadron Calorimeter (HB)**	**1,462**	**233**	**814**	**2,509**	**779**	**3,288**	**3,288**
2.1.1	Barrel	603	200	564	1,367	369	1,736	1,736
2.1.1.2	Optical System	137	168	250	555	133	688	688
2.1.1.5	Tooling	441	0	300	741	207	948	948
2.1.1.7	Prototypes	24	33	14	71	29	100	100
2.1.2	Outer Barrel	859	32	250	1,142	410	1,551	1,551
2.1.2.2	Optical System	11	0	0	11	3	13	13
2.1.2.3	Phototransducers	738	32	250	1,020	367	1,388	1,388
2.1.2.4	Electronics	111	0	0	111	40	151	151
2.2	**Endcap Hadron Calorimeter (HE)**	**1,948**	**471**	**350**	**2,769**	**990**	**3,759**	**3,759**
2.2.1	Endcap	1,387	245	100	1,732	617	2,348	2,348
2.2.1.2	Optical System	57	0	0	57	14	71	71
2.2.1.3	Phototransducers	644	45	100	789	284	1,073	1,073
2.2.1.4	Electronics	685	200	0	885	319	1,204	1,204
2.2.2	Outer Endcap	561	226	250	1,037	373	1,410	1,410
2.2.2.2	Optical System	2	0	0	2	1	3	3
2.2.2.3	Phototransducers	370	26	250	647	233	879	879
2.2.2.4	Electronics	188	200	0	388	140	528	528

US CMS NSF Cost Estimate

WBS Number	Description	US Mfg M&S (K$)	US Mfg Labor (K$)	US EDIA (K$)	US Base Cost (K$)	US Cont (K$)	Total US Cost (K$)	NSF Request (K$)
3	**Trigger/Data Acquisition**	**1,153**	**148**	**170**	**1,471**	**387**	**1,858**	**1,858**
3.3	**Luminosity Monitor**	**345**	**42**	**48**	**435**	**87**	**522**	**522**
3.3.1	Interaction Rate Monitor (2)	106	21	18	145	29	174	174
3.3.2	Beam Condition Monitor (6)	0	0	0	0	0	0	0
3.3.3	Roman Pot Detectors (6)	143	21	30	194	39	233	233
3.3.4	Power Supplies	42	0	0	42	8	50	50
3.3.5	Cables	35	0	0	35	7	42	42
3.3.6	Testing Facilities	19	0	0	19	4	23	23
3.4	**Data Acquisition System**	**808**	**106**	**122**	**1,036**	**300**	**1,336**	**1,336**
3.4.2	Readout Data Link (RDL)	313	32	122	467	135	602	602
3.4.2.1	Design and Document	20	0	48	68	20	88	88
3.4.2.2	Prototypes	28	0	37	65	19	84	84
3.4.2.3	Production	225	32	0	257	75	332	332
3.4.3.4	Installation and Test	40	0	37	77	22	99	99
3.4.3	Readout Crate Supervisor (RCS)	495	74	0	569	165	734	734
3.4.3.1	Design and Document	40	0	0	40	12	52	52
3.4.3.2	Prototypes	50	0	0	50	15	65	65
3.4.3.3	Production	405	74	0	479	139	618	618

US CMS NSF Cost Estimate

WBS Number	Description	US Mfg M&S (K$)	US Mfg Labor (K$)	US EDIA (K$)	US Base Cost (K$)	US Cont (K$)	Total US Cost (K$)	NSF Request (K$)
4	**Electromagnetic Calorimeter**	**1,845**	**147**	**214**	**2,205**	**535**	**2,741**	**2,741**
4.1	**Barrel Photodetectors**	**1,845**	**147**	**214**	**2,205**	**535**	**2,741**	**2,741**
4.1.1	Characterization Test Stand	23	10	28	60	15	75	75
4.1.2	Prototypes	0	0	33	33	7	40	40
4.1.3	Long Term Stability	21	0	86	107	17	124	124
4.1.4	Procurement and Characterization	1,796	116	48	1,960	490	2,450	2,450
4.1.4.1	Prepare Specifications and Bid Package	0	6	5	11	1	12	12
4.1.4.2	Procure APD's	1,796	0	30	1,826	457	2,283	2,283
4.1.4.3	Characterization	0	88	10	98	24	122	122
4.1.4.4	Tracking	0	3	2	5	1	6	6
4.1.4.5	Final Inspection/Test	0	20	2	22	6	28	28
4.1.5	Shipping	6	8	8	21	3	24	24
4.1.6	Project Coordination	0	13	13	25	4	29	29
5	**Tracking**	**1,265**	**282**	**860**	**2,407**	**963**	**3,369**	**3,369**
5.1	**Forward Pixel Tracker**	**1,265**	**282**	**860**	**2,407**	**963**	**3,369**	**3,369**
5.1.1	Detectors	667	0	149	816	326	1,143	1,143
5.1.1.1	Diode Arrays	667	0	149	816	326	1,143	1,143
5.1.2	FE Electronics	149	0	139	288	115	403	403
5.1.2.2	Local Control Chip	149	0	139	288	115	403	403
5.1.3	Mechanical Support & Services	449	282	373	1,104	442	1,546	1,546
5.1.3.1	Kapton Interconnect	88	43	104	236	94	330	330
5.1.3.2	Fibers, Modulators, DAQ, Pwr	193	70	45	308	123	431	431
5.1.3.3	Mechanical supports, cooling	168	168	224	561	224	785	785
5.1.5	Calibration/Testing	0	0	198	198	79	277	277
5.1.5.2	Pixel Diode Array Chip Testing	0	0	123	123	49	172	172
5.1.5.3	Data Collection Chip Testing	0	0	75	75	30	105	105
6	**Common Projects**	**3,301**	**0**	**0**	**3,301**	**0**	**3,301**	**3,301**
7	**Project Management**		**0**	**602**	**602**	**0**	**602**	**602**

References

[1] D. Green, T. Muller et al., US Collaboration for the Compact Muon Solenoid Detector, Letter of Intent, September 8, 1995.

[2] S. Reucroft et al., CMS Detector R&D, proposal to the National Science Foundation, October, 1996;
S. Reucroft et al., CMS Construction Project, proposal to the National Science Foundation, October, 1996.

[3] Interim Memorandum of Understanding for the Execution of the Initial Phase of the CMS Experiment, March 15, 1996.

[4] The Compact Muon Solenoid, Technical Proposal, CERN/LHCC 94-38, LHCC/P1, December 15, 1994.

[5] US CMS Project Management Plan, draft, September 30, 1996.

[6] Jay Hauser, *Cathode Strip Chambers for the CMS Endcap Muon System,* (Proceedings of Beauty '96 conference, Rome, submitted to NIM) CMS TN/96-140.

[7] D. Chrisman, W. Gorn, and P. Schenk, *Pedestal Subtraction, Crosstalk Correction, and ADC-Value-to Charge Conversion for the Summer 1995 P0 CSC Beam Test Data,* CMS TN/95-204.

[8] R. Breedon, B. Holbrook, W. Ko, and F. Lin, *Development of a Switched Capacitor Array ASIC for the CMS Forward Muon Chamber Readout,* (Proceedings of the First Workshop on Electronics for LHC Experiments, Lisbon, Sept. 13, 1995), CMS TN/95-132.

[9] CMS Muon Trigger Group, *CMS Muon Trigger - Preliminary specifications of the baseline trigger algorithms,* CMS TN/96-060.

[10] Yu.V. Fisyak and R. Breedon, *Comments on the Simulation of Background for the CMS Muon System,* CMS TN/96-019.

[11] J. Rowe, *CSC Detector Simulation in CMSIM 100,* CMS TN/96-68.

[12] Yu.V. Fisyak, W. Ko, and J. Rowe, *Matching Tracks in the Muon System to the Inner Tracker,* CMS TN/95-083.

[13] Yu.V. Fisyak, *Evaluation of the CMS Muon Endcap Shielding,* CMS TN/96-076.

[14] Yu.V. Fisyak, *Muon System and Central Tracker Alignment with Muons,* CMS TN/95-141.

[15] J. Rowe, *CSC Trigger Simulation in CMSIM 100,* CMS TN/96-69.

[16] R. Breedon, Yu.V. Fisyak, W. Ko, and J. Rowe, *Background LCT Rates by CSC Type Using the Forward Muon Trigger Simulation in CMS 100,* CMS TN/96-070.

[17] CMS Letter of Intent. CERN/LHCC 92-3, Oct. 1, 1992.

[18] D. Green, "Optimization of CMS HCAL Parameters Using Hanging File Test Data," FNAL TM-1894, June 1994.

[19] J. Lackey *et al.*, *CMS Calorimeter Level 1 Trigger Conceptual Design*, CMS Note CMS TN/94-284, 1994.

[20] S. Dasu *et al.*, *The Level 1 Calorimeter Trigger for the CMS Detector at the LHC*, CMS Note CMS TN/94-264, 1994.

[21] S. Dasu *et al.*, *CMS Level 1 Calorimeter Trigger Performance Studies*, CMS Note CMS TN/94-285, 1994.

[22] S. Dasu, J. Lackey, W. H. Smith, W. Temple,*CMS Missing Transverse Energy Trigger Studies*, CMS Note CMS TN/95-111, 1995.

[23] S. Dasu, J. Lackey, W. H. Smith, W. Temple, *New Algorithms for CMS Electron/Photon Trigger – Use of Fine Grain Calorimeter Data*, CMS Note CMS TN/95-112, 1995.

[24] S. Dasu, J. Lackey, W. H. Smith, W. Temple, *CMS Level 1 Calorimeter Trigger Performance on Technical Proposal Physics*, CMS Note CMS TN/95-183, 1995.

[25] "Neutron Irradiation Damage of APD's Using ^{252}Cf." S. Reucroft *et al.* submitted to Nucl Instr and Meths.

[26] Honeywell, SSEC, Plymouth, MN.

[27] "CMS Electromagnetic Readout", P. Denes, Presented at the Conference on LHC Electronics, Balaton, Sept 1996.

[28] D. Liu, R.Y. Zhu and H. Newman, *A precision Light Source and Distribution System for CMS at LHC*, CALT 68-2016 (1995).

[29] R.Y. Zhu *et al.*, *Nucl. Instr. and Meth.* **A376** 319 (1996); C. Woody *et al.*, in *International Conference on Inorganic Scintillator and Their Applications*, Delft (1995) and in IEEE/NSS, San Fracisco (1995); and R.Y. Zhu *et al.*, CALT-68-2071, in *VI International Conference on Calorimetry in High Energy Physics*, Frascati (1996).

[30] R. Horisberger, K. Gabathuler and D. Kotlinski, *Readout Architecture for CMS Pixel Vertex Detector,* CMS TN/96-046

[31] G.P. Grim, R.L. Lander, S. Mani, S. Gaalema, W. Feng, *An Analog Front-End for the CMS Pixel Detector,* (submitted to the Conference on LHC Electronics, Balatonfüred, September, 1996.

[32] CMS Cost Estimate, version 7, September 15, 1995.

[33] US CMS Contingency Analysis Procedures, September 26, 1996.

[34] On WWW, see *http://www-ed.fnal.gov/*

A US CMS Software and Computing Plan

A.1 Introduction

It is a major goal of US CMS that members be able to address the physics at their home institutions. This document was initially requested by the US CMS Management Board in its desire to understand the resource needed by the collaboration in the area of software and computing. Subsequently, it was requested by DOE/NSF as an action item arising from the FY'96 review of US CMS.

Software, computing and networks are of paramount importance to the Compact Muon Solenoid (CMS) experiment. As the detectors and the events of high energy physics experiments become ever more complex, the need for a sophisticated software and computing system has increased to the point where nowadays it is considered as a detector subsystem in its own right. In addition, computing and networks have been the enabling technology for widely spread collaborations.

Many years of intensive software development will be needed to deal with the complex problem of detecting the sought-after signals given the extremely demanding background conditions of the Large Hadron Collider (LHC). Coordination and organization of software efforts in advance of data recording have often been neglected in less complicated, lower luminosity experiments, sometimes compromising the timelines of physics results. The need for broadly coordinated and vigorous development using modern software technology is recognized by CMS. In particular, US physicists are taking on significant responsibilities for software development. Our current involvement is detailed in Section A.3.

Mobilization of computing resources is also critical for effective participation in CMS, particularly for the US groups far from the experiment at CERN. This involves synchronization of software development efforts, high bandwidth network access to experimental data, access to shared databases, documentation, and physics results, and effective means of communication, for example, by teleconferencing. Software and computing resources are vital to the experiment as a whole, and need to be supported as a coherent effort. A CMS Technical Proposal for Software and Computing (CTP) is being developed and will be submitted to the LHC Experiments Committee (LHCC) at the end of 1996. The present document is fully consistent with the drafted CMS CTP that is summarized in Section A.4. When the final CMS CTP is completed, it will be used to complement and update this document.

In Sections A.5 through A.7 we outline the computing requirements. The short term requirements are detailed in Section A.5. Long range plan and ramping-up strategy are discussed in Section A.6. A quantitative summary of the US CMS software and computing resource needs is given in Section A.7. It is envisioned that the long range strategies and requirements, as well as this document, will need to be updated every two or three years to keep pace with the rapid advances in computing and network technology.

The management of software and computing for US CMS is in the context of both the governance principle of US CMS and the software management structure of the CMS experiment as a whole. Details are spelled out in Section A.8. The US CMS software community is well represented in this management structure.

A.2 Goals of US CMS Software and Computing

The goals of the US CMS software and computing project fall into three general areas:

1. to ensure that CMS meets its physics and technical performance goals, by exploiting the US expertise in software, computing and networks to help define and manage the overall CMS software and computing project;

2. to enable US physicists to participate fully in the experiment and its future physics discoveries, while not being present full time at CERN;

3. to provide software and computing for US physicists to meet their detector commitments.

In order to meet the particular large scale needs of the CMS physics program at LHC, the experiment needs to take advantage of US leadership in many areas of computing technology. This applies both in general through US industry, and specifically in a number of areas (such as networks and databases) where HEP has the largest-scale and greatest requirements in a research environment. Much of the computing resources for the experiment will be acquired in the US. US physicists also have extensive experience in dealing with the software and computing issues for modern hadron collider experiments. This experience and expertise will play an important role in planning the computing strategies, and in optimizing the systems to be used by the experiment as a whole in terms of their cost and functionality. As a natural outgrowth of their experience in the design, implementation and operation of such systems, US physicists are already deeply involved in the definition of the overall CMS computing model and the preparation of the CMS Computing Technical Proposal.

Both computing hardware and software systems and facilities are needed for US physicists to fulfill their key roles in the development, and later the operation and physics analysis of CMS, as major partners in the experiment. During the construction phase of the experiment, computing resources are needed on a continuing basis with increasing performance levels: to optimize detector components; to perform both physics and detector-based simulation studies with increasing degrees of realism; to acquire and analyze test beam data; to acquire and record detector calibrations; and to develop physics algorithms, software and data-handling systems and procedures for data analysis. While the US efforts will emphasize the subsystems for which it is responsible, these are linked to the entire detector; thus the US needs to bear a proportionate share of the software and computing task as a whole, and to exercise leadership according to the particular areas of development and expertise of the members of US CMS.

The needs will increase sharply during the latter part of the construction period, when a production-prototype set of software, computing and networking systems must be installed and implemented prior to LHC startup. The needs will extend through the running period of the experiment, where resources will be required to calibrate and monitor the performance of detector components and to analyze detector data. This "operations" implementation will be optimized in terms of current technology and systems-concepts, with the goal of meeting the needs of the physics program and the associated technical requirements.

Ideally, US physicists at their home institutions would enjoy the same access to data as physicists at CERN. To support this access it is very likely that some US data handling facilities will be needed at CERN. Furthermore, additional computing equipment must be located at CERN for the use of US physicists while they are in residence at the experiment. The specifics of the requirements will depend on the details of the CMS computing model currently under development, as described below. While it would be premature to discuss at this stage the precise balance of CPU power, direct access disk storage, robotic mass storage, and network capability that will be required, we already know the approximate magnitude of the hardware resources required, in the context of systems now available and foreseen for the near-term future. The variation in the details of the computing model, at each stage of development of the experiment, will mainly consist of changes in the balance among CPU power, disk and tape capacity and speed, and network bandwidth, according to the cost-evolution for each major component in the model. One or more US regional centers with of order 100 TIPS of CPU power, 100 Terabytes of online storage, and 1000 Terabytes of robotic access with multi-Gigabit/sec networking are certain to be required. In addition, a small group of 5-10 software professionals should be part of US CMS efforts, working in conjunction with other such teams at CERN and elsewhere to provide the software tools and frameworks for use by collaboration physicists. In association with the use of modern technology and the work of the software professionals, modern software tools must be provided at each stage.

Finally, it is important to emphasize the importance of high-reliability high-bandwidth network access. Networks and network software and management tools are essential, not only for ensuring access to the data itself, but for providing access to the body of information required for understanding the status, monitoring and control of the experiment, and for operation of interactive communication tools that we think of as "access to the physics". New paradigms for working collaboratively at a distance will have to be developed to ensure that US physicists can be full participants in the physics. "The network", with its various local and wide-area components and interfaces, protocols and user software, is the enabling technology that will allow the new tools and modes of collaboration to work.

A.3 Current Activities, Responsibilities, and Milestones

Members of US CMS are involved in several different software efforts, and have taken responsibilities for carrying out these efforts throughout the lifetime of the experiment, including:

- design and development of portions of the current CMS simulation software framework program, known as CMSIM, and other experiment-wide software packages;
- detector subsystem trigger modeling and optimization;

- physics simulations and analyses, including background and shielding optimization studies;
- interactive detector and event visualization and analysis;
- design and development of experiment-wide computing tools and utilities, for example: data access, storage, and retrieval tools, and automatic procedures for checking and enforcing coding standards.

These responsibilities and activities are illustrated by the following descriptions of some of the current software and computing projects being carried out by US CMS members.

A.3.1 Current Software Framework, Code Administration and US Responsibilities

The current CMS Software framework, CMSIM, is summarized in Fig. A1. Major features include:

- GEANT-based simulation for all subdetectors; several levels of fast simulation trading off accuracy for speed are under development based on the full GEANT version;
- common database and file-handling system for event generation, simulation, reconstruction, analysis, and display;
- modular flow, so that subtasks may be performed independently by reading the output data structure of the previous task in the chain;
- a fully integrated interactive detector and event display system;
- background integrated into simulation to produce “Raw Data”;
- common reconstruction program for simulated and real data.

CMSIM code administration responsibilities

For CMSIM there is a general module administrator who is responsible for the coordination and synchronization of different pieces of the code. For each source file the code administrator and a few deputies from each related system are appointed by the CMS software coordinator of the subsystem.

FILE	Task	In Charge	Deputy(ies)
CMSI	CMSIM steering	Karimaki	Banerjee
DETC	Detector constants	Banerjee	...
TITL	Titles and constants	Banerjee	...
G320	GEANT geometry consistency	Fisyak*	...
UTIL	Utilities	Taylor*	...
SZPK	Zebra Bank Access Interface	Kunori*	

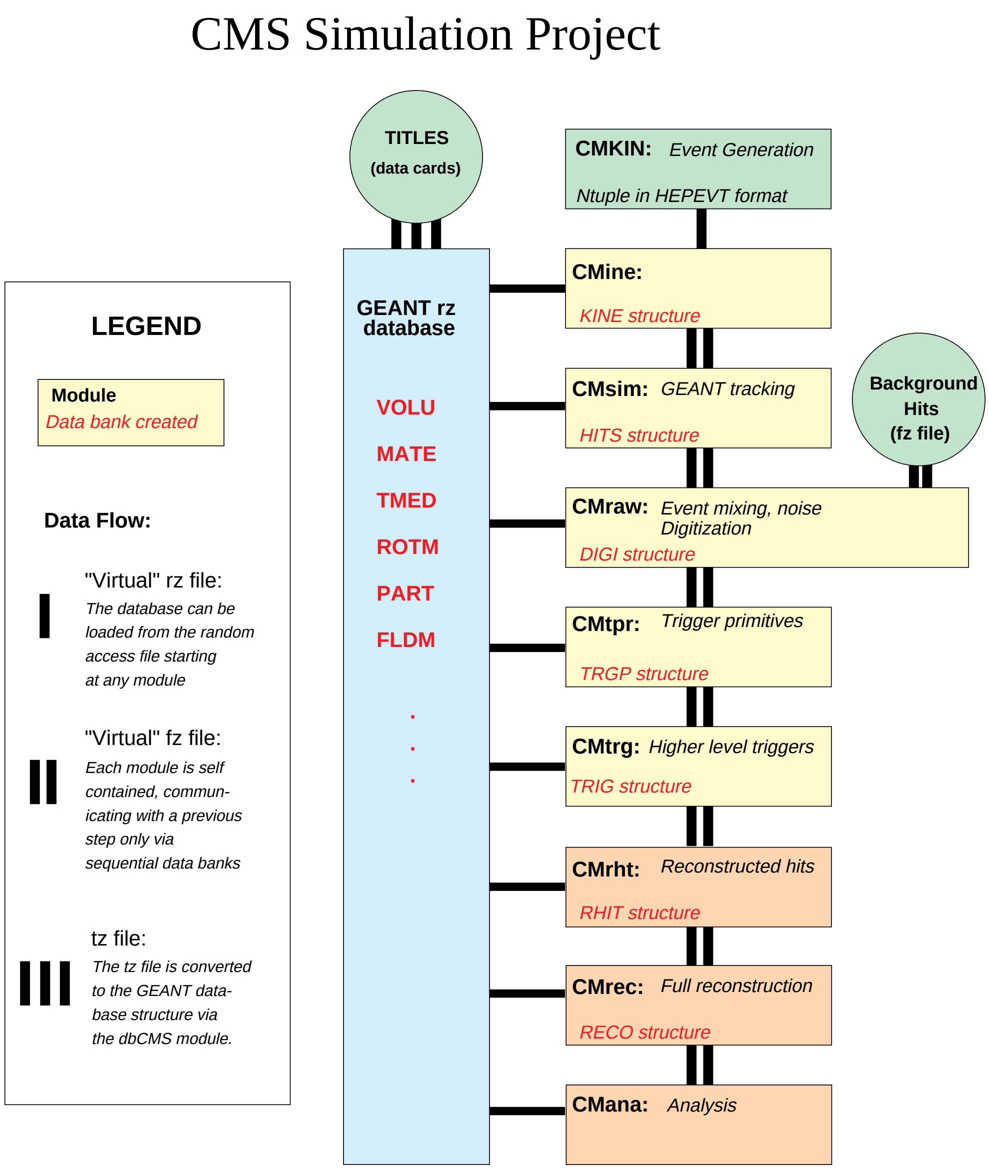


Figure A1: Flow Diagram of the CMS Simulation Project.

TRAK	Inner Tracker	Karimaki	...
ECAL	Electromagnetic calorimetry	Vialle	
HCAL	Hadronicic calorimetry	Kunori*	Genchev
VCAL	Forward calorimetry	Fouz	Litvintsev
MUON	Muon system	Ko*	Meneguzzo
MAGN	Magnetic field	Ko*	...
TRIG	Trigger	Branson*	Dasu*,Neumeister, Varela,Wrochna
RECO	Reconstruction	Karimaki	Charlot,Fisyak*, Genchev,Stanco
ANAL	Analysis	Charlot	...
SCAN	Event visualisation	Taylor*	Alverson*
BANK	Bank descriptions	Fisyak*	...
GCAL	Neutron transport	Fisyak*	...

* indicates a US CMS member.

As the list clearly indicates, US CMS collaborators have major responsibilities in the CMS software code administration.

A.3.2 Subdetector responsibilities and milestones

Muon

The US CMS group is responsible for all muon software – not only for the endcap muon system, for which US groups have major construction responsibilities, but for the entire muon system. So far, the software tasks include both optimizing the detector design and developing simulation tools for general muon software development including those for trigger studies and reconstruction. Refined geometry (that changes every time the inner detectors – tracker and calorimeters – alter their geometries), hits and digitization have been implemented in CMSIM. Trigger primitives ("Local Charged Track", LCT) and timing are simulated. The first implementation of a Kalman Filter based reconstruction program has been accomplished and the results have been used as the parameters for a fast muon simulation package.

The radiation background at LHC luminosities represents a real challenge to the muon software. We must have an as-realistic-as-possible parameterization of the background. Trigger studies and the reconstruction package must be developed with this harsh environment in mind. US CMS members are full participants in the Radiation Working Group, providing complete CMSIM simulation studies that are often very intense consumers of computing resources.

The Technical Design Report for the muon system is due at the end of 1997. In preparation for that, we have the following software milestones to meet. Following the Technical Design Report, we will start to migrate to an Object Oriented programming environment as will continue general development of the CMS software.

Dec 1996: Parameterization of neutron background; generate hit banks for charged tracks.

Feb 1997: Full muon track finding and reconstruction.

Jun 1997: Full matching of muon tracks with corresponding tracks from the Tracker.

Sep 1997: Develop software alignment plan and integrate it into the reconstruction package.

Dec 1997: Muon trigger strategy (levels 1-3) for the LHC environment.

HCAL

The US CMS HCAL group is responsible for coordinating 1) simulation studies to optimize the HCAL design, 2) software development for HCAL and 3) management of calibration data from beam tests and during hardware fabrication. These responsibilities are matched to those for the hardware construction which cover whole HCAL system.

To optimize the HCAL design, members of US CMS have already taken extensive simulations both of detailed aspects of the detector design using CMSIM and of physics processes that place requirements on the HCAL performance using parameterized HCAL response from the detailed CMSIM simulations and test beam data. Much of the simulation work will be finished before submission of the HCAL Technical Design Report (TDR) due in June, 1997, and some work to refine the design will continue.

We anticipate a shift of programming paradigm from Fortran based procedural programming to C++ based object oriented programming (OOP). We will initiate R&D of OOP-based HCAL software after the submission of TDR. In parallel to the R&D, we continue to look for improvement of algorithms in event reconstruction, mainly energy calibration, and jets and missing E_t reconstruction.

Fabrication of a preproduction prototype (PPP) will start in 1997 and fabrication of HCAL modules will follow. The PPP will be in a test beam in 1998. Management of calibration constants during hardware fabrication and from beam tests is a key for accurate energy measurement in the CMS experiment. We will pay special attention to it throughout the hardware construction phase.

Milestones until 2000 are as follows.

Jun 1997: finish simulation studies to finalize the HCAL design for TDR and PPP.

mid 1997: initiate R&D for future HCAL software based on OOP.

1998: support beam tests with PPP.

2000: migration of HCAL software and database to new OOP-based framework.

Tracking with forward pixel detectors

The forward pixel detector and its associated software are the responsibility of US CMS. This will include simulation studies (in the CMSIM framework) of alternative design options, in close collaboration with the US groups working on the design and construction of the hardware. Many, but not all, problems are common to both the central and forward pixel systems. We will continue to cooperate closely and share tasks with collaborators such as PSI, Zurich, who work on software for the barrel pixels, to avoid duplication of effort.

The US will also contribute to the overall track reconstruction software. In conjunction with the trigger/DAQ group, there will be some work on tracking algorithms suitable for use in the second or third level trigger. The forward pixel milestones are as follows:

end 1996: preliminary or stand-alone evaluation of alternative forward pixel designs, clustering & resolution studies.

end 1996: Interface of a Kalman Filter based track finding algorithm, originally developed for SDC and the D0 upgrade, to the main CMS simulation and reconstruction program.

mid 1997: Evaluation studies of the above track finding algorithm.

1997: Full evaluation of alternative forward pixel designs embedded in full, detailed simulation of the entire tracker, at high luminosity, with particular emphasis on impact parameter and secondary vertex studies.

1998: Participation in the development of an object oriented version of the CMS software; implementation of an OO version of pixel simulation and reconstruction.

2000: Preparation of pixel-related simulation, calibration and reconstruction software in the final CMS software environment.

A.3.3 Interactive Graphics Display

Menu-driven interactive graphical displays provide physicists with an invaluable tool during all phases of the experiment. With the increasing complexity of modern experiments, particularly those at high luminosity hadron colliders, and the availability of relatively inexpensive high-end graphics workstations, the role of such software has steadily increased. It is anticipated that CMS will heavily exploit the possibilities afforded by this kind of software.

The detector and event visualization program will

- aid the design and optimization of the detector sub-components and overall detector configuration;
- facilitate tuning of the detector to physics signals by providing optimized physics reconstruction algorithms;
- help in debugging of the software, the detector geometry, the reconstruction algorithms (particularly those which use data from more than one subdetector), and ultimately the behavior of the detector itself and the readout system;
- enable the physicist to develop invaluable insight when trying to extract rare signals from potentially overwhelming backgrounds.

The single most important view is the 3D cartesian representation of the detector and event data, with arbitrary magnification, offset, rotation, clipping, and visibility. The view is projected into 2D although the implementation of true 3D, for example using stereo views, is not ruled out for the future. Visualization does not, however, consist merely of such views. Transformed views of event data play a crucial role in our ability to assimilate the important features of events. For example, jet structures are clearly seen in a "lego" plot of energy as a function of azimuthal angle and pseudo-rapidity. The physicist may imagine many useful transformations Euclidean, Lorentzian, etc., and an event display program should be prepared to support such views. The beam crossing time of 25 ns at the LHC renders both inter- and intra-event times crucial for triggering and reconstruction. This adds a "fourth dimension" which needs to be considered in the context of event visualization. In addition to viewing the events, the physicist needs to be able to interact with the data structures which are displayed, for example to refit tracks which appear to be kinked due to decays in flight or to display derived quantities specific to his or her analysis. To be able to provide such functionality, the event visualization program must be integrated with the simulation, reconstruction, and analysis programs while at the same time allowing intuitive and real-time access via an appropriate graphical user interface. This includes the ability for the user to select graphical objects on the screen, view the associated results of the reconstruction program at various levels, and to trigger re-reconstruction of selected portions of the event. These features are important to test the results of new software and/or calibrations, to explore the nature of unusual events, and to localize and troubleshoot detector problems.

The US is responsible for providing the detector and event visualization software for CMS. A prototype visualization program, known as CMSCAN, is under development. It has an intuitive X11/Motif interface with extensive functionality to enable the physicist to manipulate the image (rotate, translate, magnify, select visibility, etc.). It is anticipated that in the coming years CMSCAN will develop into a fully-fledged "SCAN" program for the visualization and analysis of CMS events. CMSCAN is currently based on the Phigs ISO/ANSII 3D graphics standard but it has been designed in a modular fashion to facilitate the transition to future standards, such as Open GL, or even new paradigms, such as Java. Object Oriented programming developments, in particular the developments taking place within the GEANT4 project, are being monitored so that the graphics may be closely integrated with GEANT-based CMS simulations as well as the rest of the CMS reconstruction and physics analysis chains.

A.3.4 Physics Studies

The fundamental physics goal of CMS is to uncover and explore the physics behind electroweak symmetry breaking. This involves the specific challenges to

- Discover or exclude the Standard Model Higgs and/or the multiple Higgses of supersymmetry;
- Discover or exclude supersymmetry over the entire theoretically allowed mass range; and
- Discover or exclude new dynamics at the electroweak scale.

The energy range opened up by the LHC gives us the opportunity to search for other objects, for example to

- Discover or exclude any new electroweak gauge bosons with masses below several TeV; and
- Discover or exclude any new quarks or leptons that are kinematically accessible.

Finally we have the possibility of exploiting the enormous production rates for certain standard model particles to conduct the following studies:

- The decay properties of the top quark, limits on exotic decays such as t $\rightarrow$ c Z or t $\rightarrow$ b H^+ (with $H^+ \rightarrow \tau + \nu$).
- b-physics, particularly that of B-baryons and B_s mesons.

An LHC experiment must also have the ability to find the unexpected. New phenomena of whatever type will decay into the particles of the standard model. Performance of CMS in response to the lists given above must be studied extensively in the detailed design of the detector. The varied physics signatures for these processes require the ability to reconstruct and measure final states involving the following:

- Charged leptons including the τ;
- The electroweak gauge bosons W, Z and γ;
- Jets coming from the production at high transverse momentum of quarks and gluons;

- Jets that have b-quarks within them;
- Missing transverse energy carried off by weakly interacting neutral particles such as neutrinos.

In our simulations of physics signals and backgrounds, we use perturbative QCD to estimate production cross sections for both signal and background processes. The level of simulation used varies quite widely. For a few processes a fully detailed GEANT simulation has been carried out. Such simulations are very CPU intensive (as much as 100 mips-hours /event) and are therefore difficult to carry out for processes where large number of events need to be simulated and many strategies for extracting signals need to be pursued. In these cases a particle level simulation and parameterized detector response (based on test beam data or full simulation results) is employed.

Specific physics simulation studies that are carried out by the US groups include

a) Tau lepton identification

> The leptonic decays of tau, produced in W or H decays, into electron or muon are difficult to separate from direct W leptonic decays on an event-by-event basis. The semi-hadronic decays of tau, with a total branching ratio of about 64%, predominately produce narrow one or three prong jets, which can be efficiently detected over the large QCD jet background. In CMS, because of large particle densities at high luminosities, tau jets may prove harder to separate from QCD jets. Simple selection criteria do not reduce the QCD background to sufficiently small levels. The various characteristics of a tau jet, such as one or three charged track multiplicity, collimated energy flow, high pt leading track, etc. should be combined into a tau-likelihood to take full advantage of all available information. We plan to develop and study such a likelihood method using simulations of the CMS detector. The process t$\rightarrow$ H^+ b; $H^+ \rightarrow \tau^+\nu$; $\tau \rightarrow$ hadronic jet serves as a physics benchmark to measure the performance of such tau-likelihood method.

b) New Heavy Vector boson production

> The limit of the muon system is tested against the capability to measure heavy vector bosons. Many extensions of the standard model include additional heavy vector gauge bosons. The largest set are SO(10) or E_6 GUT models. The models with the largest cross sections, the left-right symmetric and alternative left-right symmetric models, both contain an additional heavy Z' boson. We have investigated the discovery potential for a Z' from either of these two models by the CMS detector, using an improved parameterization of the muon system track resolution.

c) Strong WW scattering

> The strength of the WW interaction depends on the mass of the Higgs boson and violates perturbative unitarity for Higgs boson masses in the neighborhood

of 1 TeV. If there is no Higgs boson, WW scattering becomes a strong interaction for WW center of mass energies of about 1 TeV and an excess of events will be observed. This is a challenging signal because of the low event rate and high lepton momenta. An intuitive representation of the physics signal was compared with backgrounds. With 100 inverse femtobarns of data we conclude that a signal with a statistical significance of approximately 3.1 sigma is detectable.

d) Missing E_t

To optimize the design of the hadron calorimetry, we have already undertaken extensive simulations both of detailed aspects of the detector design (using GEANT) and of physics processes which place requirements on the HCAL performance. Examples of the latter are the detection of supersymmetry through missing transverse energy plus jets. We conclude that CMS will be capable of observing supersymmetric particle production in this final state for all reasonable choices of super-partner masses. We have also investigated the effects of various detector imperfections (cracks, nonlinearities, etc.) on our ability to detect a signal and this work will necessarily continue as the design of the HCAL is optimized. The supersymmetry study required about 200 runs of order 1 week on Silicon Graphics machines = 1M mips-hrs. We expect to carry out a few such studies per year. We have also investigated the ability of CMS to observe a high-mass standard model Higgs in the channels H$\rightarrow$ ZZ$\rightarrow$ $\ell\ell\nu\nu$ and H$\rightarrow$ WW$\rightarrow$ $\ell\nu$ jet jet. These processes test the detector performance for missing E_t and for dijet mass reconstruction. It is also found that the signal to background ratio can be significantly improved (though at the loss of signal efficiency) by using forward-going jets as a tag of Higgs production, which puts requirements on the forward calorimeter performance.

A.4 The CMS Software and Computing Plan

The CMS Collaboration is in the process of writing the CMS Computing Technical Proposal (CTP) which will be ready by the end of 1996. The CTP was formally requested by the LHCC. This request was welcomed by CMS because of the recognized need for a plan which would set directions for the CMS software effort and provide sound estimates for the resource requirements over the next decade and beyond. It is planned to update the CTP at regular intervals throughout the construction of CMS.

Members of US CMS are full participants in the preparation of the CTP, and are leading both the preparation of the document and the systems design and planning behind it in several areas. It is expected that the CTP released at the end of 1996 will both reflect the interests of the whole of CMS and have the full support of US CMS. The present document contains preliminary plans and preliminary estimates of resource needs. The plans and resource estimates presented here are consistent with the overall plans presented in the CTP. It should be understood that updated information will appear in the CTP and in subsequent updates to the CTP in later years.

The CMS Computing Model is the name given to the outline plan describing how software, networks and hardware will support a timely and competitive analysis of CMS data by geographically distributed CMS physicists. The current model has these key elements.

- A move towards mainstream software engineering techniques for the construction and maintenance of CMS software. The current mainstream has been identified as Object Oriented Analysis and Design.
- Maximizing the use of commercial software, especially commodity software wherever applicable (e.g. data storage and retrieval).
- Use and collaborative creation of common HEP software, such as GEANT4 (Object Oriented Simulation Toolkit), whenever the needs are not CMS-specific, but not general enough to attract the commercial software industry.
- Maximizing the use of commodity hardware. The future desktop system will be the successor to today's PCs. In contrast, commodity solutions for petabyte storage and access are not currently available.
- Creation of a coherent worldwide physics analysis environment. This requires an optimized interworking combination of CERN-site data storage and processing, wide-area networks, regional and university data caching and processing, and the physicist's desktop workstation. The nature of the optimum combination will depend crucially on the wide-area network bandwidth which can be bought for a tolerable fraction of the total expenditure on computing.
- Excellent inter-personal communications tools to complement the coherent worldwide physics analysis environment.

Although the quantitative details of the optimized distributed analysis environment are uncertain and will change with time, it is certain that the optimum will require software, networking, desktop and university systems, regional centers, and CERN-based systems. A simplified but plausible prediction for CMS data processing comprises the following.

- Systems at CERN serving the needs of the whole collaboration for first pass reconstruction and petabyte storage. The first pass reconstruction might be relatively unsophisticated but must extract the key features of each event for entry in the 'Event Tag' database.
- Regional centers, primarily Fermilab in the US, providing
    1. mass storage (disk+tape) cache automatically managed;
    2. processing power for data-intensive analysis;
    3. half the simulation facilities;

4. a proportionate share of expert personnel and maintenance support, scaled to regional needs, for computing hardware systems, network access, operating systems and software libraries, reconstruction and simulation "production" and development.

- University group systems with disk cache, retrieving data as necessary from or via their regional center. Most decisions to access data will be based on information extracted from the Event Tag Database. The bulk of the Monte-Carlo work is expected to be developed and performed by the university groups. Major simulation and data analysis centers in the universities are envisioned.

- Networks linking all systems. The existence of the University and Regional Center data cache is based on the reasonable assumption that the university group LAN offers much more throughput than the University-Regional Center WAN which offers much more throughput than the Regional Center-CERN WAN.

- Data Storage and Processing, including local and wide area communications, are the central elements of the Computing Model, and thus are expected to constitute the major part of the computing equipment cost.

The data-storage, networking and processing power needed to analyze CMS data are well in excess of those of today's facilities. Technological advances will make CMS data analysis possible, but the optimum mixture of storage, networking and processing will change continuously. The way this mixture will work together is called the 'CMS Computing Model'. The model must retain the flexibility to take advantage of most or all of the changes in hardware and software technology which will happen in the next 20 years. Given this timescale a realistic model must necessarily contain ambitious elements. A simple example of the CMS computing model is shown in Fig. A2. For clarity, numerical values are given for the storage and processing power which may be used in the first years of data taking. The regional center interposed between universities and CERN is particularly advantageous if network communications within the region are economical, while those between the region and CERN are more costly.

A.5 Short Term Computing Requirements

By the end of 1997, the Technical Design Reports of most subsystems are due. The software and computing support for completing the subsystem Technical Design Report is the highest priority task in the short term. US CMS groups are already making good use of existing computing resources at Fermilab and universities (in roughly 50/50 ratio). Many physicists are devoting significant portions of their research time to CMS software, supported out of base program funds and benefitted from the travel supplement for CMS from DOE's university program. Our short-term plans revolve mostly around using the existing resources to maximize the impact of physicist time devoted to CMS.

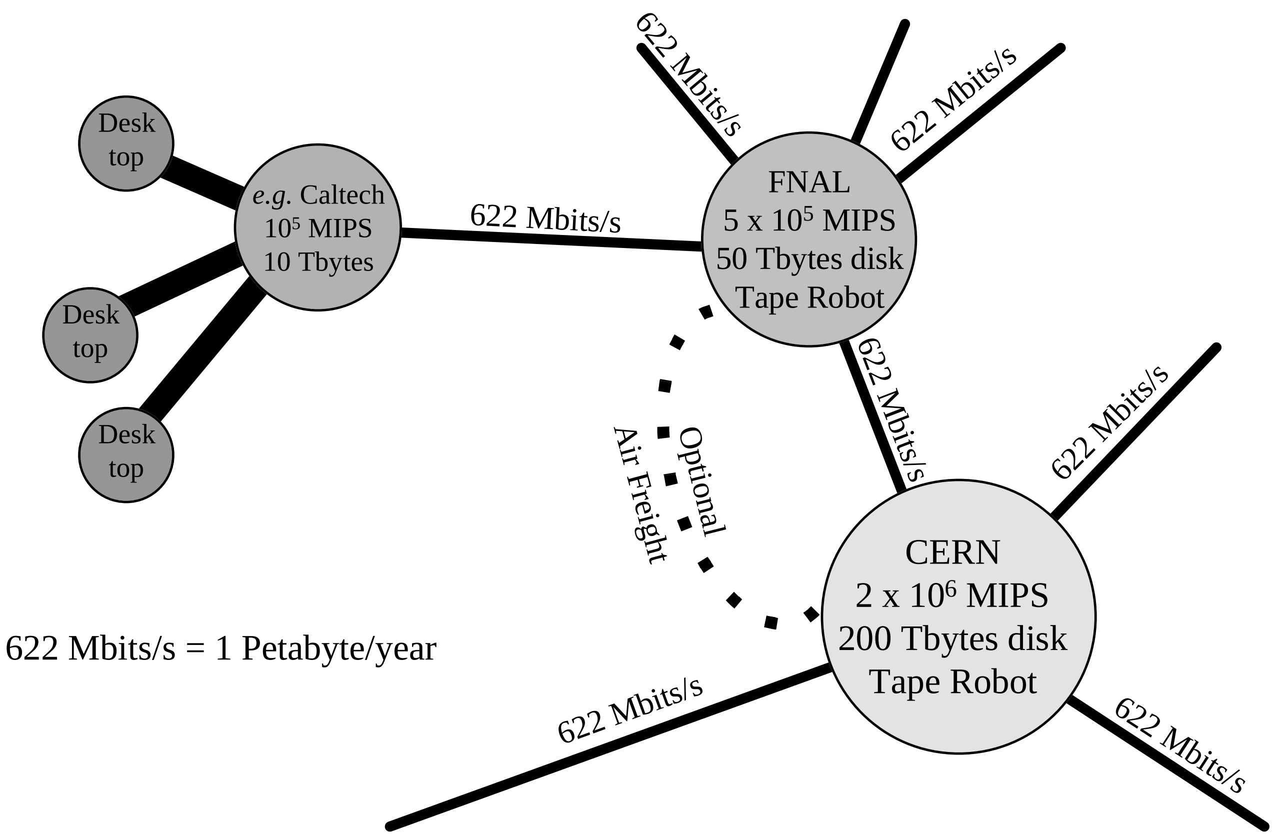


Figure A2: A Simple CMS Computing Model.

A.5.1 Major production resource requirements

Associated with the US responsibilities in CMS software are substantial computational requirements. The current major production tasks are

	MIPS-Hours
(1) Endcap Muon Background Simulation	10 M per configuration
(2) Trigger Simulation Production	10 M per production
(3) HCAL Simulation and Physics Studies	6 M per year
(4) ECAL Detector Simulation Study	5 M per study

The computational needs are being met but studies take a few times longer than desirable. As described later, the needs are increasing significantly. A detailed description of these jobs is shown below.

(1) Endcap Muon Background Simulation Studies

The muon system receives background hits from secondary decay muons as well as punchthrough hadrons and from charged particles originating from neutron capture by nuclei. The latter source is especially likely to be a significant contribution to the occupancy of the muon system because of its large detector elements.

With final verification of the software and geometry nearing completion, the next step in the development of the simulation itself is to incorporate the background. This will enable comprehensive studies of triggering and off-line muon reconstruction under realistic conditions, where hits are subject to pileup and multiple hits are registered in detectors.

Two separate simulation streams of high statistics for punchthrough and neutrons were performed using different event generators and cuts to emphasize separate backgrounds. From these two simulation streams, respectively, background simulation is being installed in the following forms:

1. Files of hits of charged particles originating from muons and punchthrough available to combine with generated primary event hits, and
2. Backgrounds originating from neutrons are parameterized, yielding energy and hit rate spectra to simulate pileup at any expected level.

For these parameterizations, high statistics are required. Because even low energy neutrons can generate gammas in the MeV range, neutrons must be traced essentially to zero kinetic energy. For other hadrons we use a cutoff of 1 MeV. For electrons and photons we use the lowest possible cutoff for electromagnetic processes permitted by GEANT: 10 keV. These low cuts set the requirements for CPU time.

There are in addition decisions that will soon be cast into steel regarding the detector and shielding design that require extensive simulation. These include backsplash from the forward calorimeter into the lowest part (highest η) of the muon endcap chambers and from the beam collimator into MF4 through the shielding in front of the low-beta quadrupoles. Some studies require prompt answers that need be completed in a few days, so our computer usage may be intense but intermittent.

(2) Trigger Simulation Production Plan

Simulated data are required to finalize the level 1 trigger algorithms before hardware designs are frozen. In addition, we need to develop and understand level 2 algorithms, which will influence level 1 hardware design. We do not want to build features in level 1 to save data that will be difficult to use in level 2.

We need to generate about 300,000 events of the types described below. The time per event varies greatly with the multiplicity of the event. The average time for one event is approximately 33 mips-hrs [three events per hour on a 100 mips Alpha or HP 9000/730 or two per hour on a 65 mips SunSparc or IBM RISC6000] resulting a total need of 10 M mips-hrs. As for the disk we estimate 200kB per event assuming that tracker data is highly compressed. That will result in 60 GB. The data should be made available on Exabyte or DDS2 cassettes for distribution to various trigger institutions.

- 150000 QCD 2-jet events distributed among various pt ranges from 10 GeV to 1 TeV to estimate trigger rates and to measure jet efficiency.
- 50000 Minimum bias to be combined with QCD 2-jet events and signal events.
- 100000 Signal events.

10000 events each for various signals such as

t$\rightarrow$ electron + X	(to measure single electron efficiency)
H (80)$\rightarrow$ 2 photons	(to measure diphoton efficiency)
SUSY H(M,tanβ) $\rightarrow$ 2 τ	(to measure τ efficiency)
WW production	(to measure dielectron, electron+muon efficiency)
Drell-Yan Z	(to measure generic Z efficiency)
Drell-Yan W	(to measure generic W efficiency)
B $\rightarrow$ electron + X	(to measure B physics efficiency)

(3) HCAL Simulation And Related Physics Studies

The computing activities by the the CMS HCAL group, including the forward calorimeter have been centered at Fermilab. Major goals of the computing activity are a) to finalize the

HCAL design for the HCAL TDR due in June, 1997, b) to demonstrate physics potential with the HCAL design and c) to initiate R&D for future HCAL software. Major activities we anticipate in 1997 are the following:

1. analysis of test beam data and simulation for the test beam setup;
2. mapping of calorimeter response for single particles in Pt-η space;
3. performance study for physics processes relating to Hadron calorimeter;
4. R&D for future HCAL software.

The computing resources needed at Fermilab are shown below.

- CPU: 5M mips-hrs/year (to be split roughly to 1:3:10 for activities 1, 2 and 3, respectively)
- DISK: additional 20 Gbytes to current 8.8 Gbytes (total 28.8 Gbytes to be split roughly 3:1:10 for activities 1, 2 and 3, respectively)
- Tape: support for easy file spooling between tape and disk for data archive/retrieve.
- Special software for HCAL software R&D: C++ compiler, CASE tool for Object Oriented Programming.
- MBone support on workstations in the CMS office area at Fermilab.
- CMSIM library management on the fnalu cluster and workstations in the CMS office area at Fermilab.

(4) ECAL Detector Simulation Studies

The following strict performance requirements of the CMS electromagnetic calorimeter arise from the need to detect an intermediate-mass Higgs boson decaying into two photons:

1. the best possible energy resolution;
2. the optimal value for the offset in crystal angle;
3. the effects of photon conversions; and
4. different regions in rapidity.

The goal of these studies is to optimize the current Higgs detection efficiency and mass resolution and to determine if there is a need for design modifications.

A.5.2 Evolution Of Computing Requirements

In comparison to the problems specified above, the simulation needs in the near future will be increasing steadily. Large sets of signal and background events must be simulated and reconstructed using the CMS design which will be finalized in the next year for each subdetector. Increasing amount of details of the detector must be simulated. While fast simulations using smeared four-vectors, as well as more detailed representations of events using techniques such as frozen shower libraries and/or idealized geometries are planned, a large number of fully simulated events are needed to establish the validity of the fast simulations, and to ensure that non-ideal regions such as the barrel-endcap transitions are adequately represented.

The trend towards more realistic simulations and larger event samples is firmly established within the collaboration. This is reflected also in the 1997-1999 CMS computing resource request to CERN. In order to satisfy simulation, central test beam data recording and test beam analysis needs, approximately 4 times as much CPU power for 1997 as for 1996 is required, as well as 500 Gbytes of disk space and approximately 5 Terabytes of tape storage for 1997. Further increases are foreseen in 1998 and 1999. Acquisition by CERN of one or more large SMPs (Symmetric Multiprocessor Systems) to meet these needs is under consideration. Maintaining the balance in the breadth and significance of studies performed by US CMS, as a major collaborator in CMS as a whole, would require appropriately scaled resources from Fermilab, and from the university program where available.

A.5.3 Other resource needs and software professionals

In addition to major simulation productions, resources are needed for:

1. US physicists at CERN, such as workstations, servers and X-terminals;
2. software licenses for US computers to allow US physicists at home to take part in various software development activities. The transition to new object oriented programming methodologies in particular will require an investment in commercial software tools.

The modest expansion of computing resources provided by US CMS collaborating institutions out of base-program funding is needed for the critical CMS-related work by US groups.

Important tasks for US CMS software professionals in short term include:

- management, coordination, and support of the CMS software environment (beginning with CMSIM) for US physicists on a variety of computing platforms;
- improvement of the throughput for simulation production to ensure the simulation tasks for the subsystem Technical Design Report are fulfilled;

- preparation and execution of training programs to prepare US physicists for the transition to new object oriented (OO) programming methods;
- participation in the evaluation and selection of development tools, design of software structures, and trials of OO development schemes on specific sectors of CMSIM simulation and reconstruction codes, and distributed OO databases.

A.6 Long Range Plan and Ramping-up Strategy

Concept of the Long Range Plan

The US CMS long term plan aims at providing an efficient computing and networking environment in support of cooperative data analysis, software development, and daily information exchange, spanning several technology generations. The plan is a coordinated part of the plan expressed in the Computing Technical Proposal for CMS as a whole, with a focus on the particular expertise of the US sector of the collaboration in the planning and development of computing, networking and software systems. While the US CMS plan includes an emphasis on the areas where the US has primary responsibilities, the physics interests and the related computing and analysis tasks are global, covering all subsystems of the experiment.

The concept of the US and overall CMS long-range plan for computing is based on the use of "modern" computing and software technology, and of current data handling and analysis methods at each generation. The rapid advance of these technologies is expected to make it possible to carry out the overall computing task effectively, and ultimately to exploit fully the physics opportunities at the LHC, with computing resource per physicist in-line with that experienced in the largest experiments in operation today. As experience in today's large HEP experiments has shown, a flexible plan that adapts continually to recent changes in computing, software and networking technology and methods is essential for cost-optimized and effective development of the detector and its data analysis by a worldwide-distributed physics collaboration.

The plan encompasses several phases, from the present pre-construction phase to early operations and physics analysis using real data a decade from now. During this period, based on the experience and technology-tracking data of the last 15 years, the performance per unit cost of computing systems is expected to increase by a factor of at least several hundred, and the network bandwidth per unit cost is expected to continue its steady exponential increase. These expectations are the basis of the CMS Computing Model mentioned in an earlier section.

It is the explosive advance of technology that will make it possible to exploit the discovery potential made available by LHC's combination of high energy and luminosity, with resource requirement for software, computing and networks that is similar to present-day experiments in terms of the fraction of the total project. The technical requirements will rise over the next decade to include the installation of systems handling data volumes, data recording and access at rates of many gigabytes per second, and distributed coherent databases presenting a unified "image" of the data over worldwide networks at typical speeds of gigabits per second. As a result of technology changes during the same time period, however, the overall complexity and level of effort required for the physics analysis task are expected to increase only linearly, and to be matched to the size of the CMS collaboration. The complexity and personnel requirements of the CMS computing task are thus set by the features of CMS's subsystems, trigger and readout, and the particular analysis problems of detector calibrations and reconstruction that are associated with the high rate and radiation environment and the multiple interactions per LHC beam crossing, and not by the number of readout channels or the quantity of stored data.

The plan for computing hardware systems is thus evolutionary, and is based on continual upgrading of system-types until the scale required for LHC operation at full luminosity is reached. The software requirements are more rigorous, and often revolutionary, in order to achieve a level-of-effort for the individual physicist similar to present experience. The use of software, data handling, simulation, reconstruction and visualization tools and techniques that are "current" in each generation will inevitably entail radical shifts in working methods. The shift to Object Oriented Analysis and Design techniques, and C++ code, is one example.

The near-term computing task is centered on detector design and physics performance studies, which will be a principal focus of effort until the subdectector designs are mature and detector construction is well underway. The medium term will be dominated first by the planned paradigm shift in software and thus in working methods and modes of communication, followed by the analysis of simulated data using the newly engineered software with a continually-increasing degree of reality and scope, where the data sample sizes and/or level of detail in the simulations and reconstruction will be moderated by the available processing and data handling resources. This process will evolve over the longer term into complete and robust reconstruction, simulation and analysis of full events as LHC startup approaches. A rapid ramp-up, trials and shakedown of the full set of production-prototype computing and software systems is foreseen approximately two years before the startup date.

Principles of US Participation

In order for the US CMS effort to be effective, each collaborating institution must have access to central and regionally stored data, and to the rest of the CMS collaboration. The speed of local, regional and transatlantic data access must make the physicist's working efficiency in doing data analysis in the US similar to that experienced by physicists based at CERN. Moreover US CMS must have the computing resources to support simulation, calibration and analysis of the CMS detector, with an emphasis on the subsystems for which it is responsible. For CMS physics analysis to be successful the computing and networking infrastructure should support collaborative work by geographically distributed analysis groups, both through data sharing and teleconferencing for daily communications.

The above needs will require computing and networking systems in the US able to interoperate closely with the CERN infrastructure. US CMS is heavily involved in the design and use of the CMS computing infrastructure at CERN, particularly systems for large scale data handling, and in the operation, installation and future planning for transatlantic networks which will serve the whole CMS collaboration.

Computing systems meeting the specific needs of US CMS should be installed in the US when technically feasible. A large part of the US needs and contributions to simulations are expected to be met by systems in the US, using existing resources of the base program and host institutions as much as possible. The future cost and performance for intercontinental networking will determine the extent to which computing resources for reconstruction and physics analysis based in the US would optimize the productivity of US CMS. A flexible approach to the location of these resources would maximize their cost-effectiveness.

US CMS will also continue to play a strong role in the design, implementation and support of principal elements of CMS software. This includes the software toolkit used to develop the main body of the Level 3 trigger, simulation and reconstruction, and physics analysis software. The life-span ($>$ 20 years) of this software mandates a cohesive, well coordinated effort with a professional approach to the management and execution of the software project. A team of full time US professionals with a long term commitment to CMS software is needed, equivalent to approximately ten computing professionals. The majority of this team should preferably be based in the US. Locating a reasonable fraction of the entire team at a single site will facilitate the necessary exchanges of information between team members and should best utilize the expertise and support from existing personnel. Locating team members at other sites with significant computing and software responsibilities is also expected, especially where there is significant use of local expertise and support.

Fermilab as the Host Laboratory of US CMS

The Fermi National Accelerator Laboratory has agreed to act as host laboratory for the US groups in CMS. Fermilab is an active high-energy physics laboratory, and is presently operating the world's highest energy particle collider, the Tevatron. The laboratory has a good infrastructure, substantial hadron collider experience due to its two running experiments, CDF and D0, test-beam facilities, and a Computing Division experienced in high data volume and CPU intensive computing.

In addition to acting as the host-site for many of the software and computing efforts based in the US, Fermilab will be a major (and likely the largest) regional center for CMS computing outside of CERN. In addition to providing for large scale computing for CMS at Fermilab itself, the US CMS host laboratory needs to (1) provide computing and data resources, software and communications services and support to US CMS groups wherever they are based, in coordination with other US CMS institutions with computing resources; (2) carry out a broad range of software and systems development tasks, in coordination with US CMS software groups; and (3) jointly provide a consistent set of cost-effective computing, software development, database and software-base support services, in coordination with CERN, other regional centers and individual groups throughout CMS.

Robust and high performance networks connecting each of the US CMS institutions to Fermilab and to each other, and from US CMS to CERN, are crucial in allowing the US CMS physics groups to fulfill their respective roles. The network connection between Fermilab and CERN is of particular importance in allowing Fermilab to fulfill its role as US CMS host laboratory, and as one of the principal regional centers for computing in CMS.

The Fermilab Computing Division is already providing valuable support to the US CMS groups. Short term needs have been addressed so that US physicists can fulfill their detector commitments, such as the trigger, data acquisition, and physics performance simulation studies that must be completed before CMS enters the construction phase. These needs are prioritized and presented to Fermilab by the US Software and Computing Board (USSCB) under the auspices and with the consent of the US CMS management.

For the Tevatron Run II, Fermilab anticipates a 20-fold increase in data volume from both of its collider experiments. This will bring the amount of data closer to the anticipated CMS volume than any other high energy physics collider experiment. The experience gained in the development and use of data handling and access strategies implemented for Run II will be valuable in the planning of CMS. This experience could provide important directions, and perhaps some of the elements of a future common solution for data handling at the LHC. Exploring common computing interests, and close collaboration on specific projects is of high interest.

Other US CMS Institutions and Regional Centers

The bulk of the software development in the US is done by University groups. Moreover, half the computing resources are provided by the computing infrastructure of these groups. Adequate and continuing support in the base program to maintain, support and upgrade the university computing resources is essential to the CMS effort.

Some US institutions are involved with research and development projects to use commodity products (such as PC systems and components) to build up simulation farms as well as desktop environments. Although the details of a future “optimal” computing environment for HEP experiments are still unknown, it is very important to explore and better understand the role of low cost mass-market processing, data storage, and I/O systems in the overall distributed system architecture for the LHC. Related key issues are the scalability, robustness and long-term survivability of operating systems used in PC platforms in a large scale collaborative research environment, where a study of the characteristics (advantages and limitations) of operating systems could provide important information for the planning and design of future mainstream HEP systems.

Collaboration with non-CMS institutions to solve some of the common problems of computing is important. The development of new modes of computing, data handling, data communications and teleconferencing has and will continue to involve close collaboration among university HEP and non-HEP groups, and among universities, outside laboratories and vendors’ research groups. This branch of development of new methods of computing, for HEP and other DOE and NSF supported research disciplines, could have an important role in developing resources in areas that would not otherwise be available to the HEP community. US CMS maintains an open policy for such collaboration and partnership.

Access to efficient networking within the US and across the Atlantic is a basic requirement for effective participation of all US groups. The development, installation and upgrade of these networks are high priority items. University groups need to have efficient ramp onto high band-width network (for example tail-circuit to ESNET). Every effort will be made to work with appropriate agencies to establish and keep up with the state of art network to access CERN and Fermilab as a regional center.

Ramp Up and Transition Strategy for Software

CMS is committed to the transition from its current Fortran based software to object oriented software. Object oriented (OO) programming techniques should allow the CMS software to be modular and maintainable during the lifetime of the experiment. To accomplish this transition the whole approach to software design needs to change, since re-coding Fortran logic in C++ or any other OO language would achieve nothing.

The existing Fortran software for simulation and analysis is in constant use and development to meet the needs of the CMS detector design. This vital work cannot stop and should continue at full speed. We believe that the best time for a systematic transition to OO programming will be after the technical design reports for each detector subsystem are due. The timing for the transition is based on the initial exploratory projects using OO design concepts and methods in C++ programs which are now underway, and is consistent with plans for GEANT4, a principal component of the common HEP object oriented toolkit. The first usable but still incomplete version of GEANT4 is on track for early 1997. A complete transition to an Object Oriented simulation program should be possible after 1998.

Ideally, parallel team efforts would make this transition more efficient. However this is prohibitive in terms of the available personnel. A small OO task force exists now and is encouraging CMS physicists who are about to write new software to use OO techniques. By the beginning of 1998 many CMS physicists will have experience with the new technology and should be able to switch to the new simulation and reconstruction framework. The use of OO subsystems within the existing Fortran framework will be encouraged, but brings the risk that the design of these subsystems will be seriously flawed. This risk is considered acceptable in view of the value of the experience to be gained and the practical certainty that such code will be re-designed before the start of LHC.

Ramp Up and Transition Strategy for Computing Facilities and Network

During the construction phase, the computing facilities for CMS must support detector design, test beams, software development, and communication. Although central facilities will be required at CERN and at regional centers, a substantial fraction of the resource needs relate to workstation clusters, commercial software and wide area network (WAN) links. Many needs, such as those for workstation clusters at US CMS institutions and networks linking them may be hard to disentangle from those of running experiments. We thus foresee a steady transition based on the changing focus of the CMS groups from running experiments to CMS as the running experiments slowly wind down. This will provide some utilization of resources in the base program, assuming that university and laboratory facilities continue to receive adequate support and are periodically modernized.

Some refitting and redesign, as well as upgrading or replacement of some of the hardware and software components of the CMS computing environment must also be foreseen, in response to changes in technology and working methods that are maintainable during the long period of construction of the experiment.

Two years before the start of full LHC operation will be a critical period for the CMS computing efforts. The demand on central and regional facilities should increase dramatically as CMS makes the transition from construction to the operational phase. At this time, final tests and development of the coherent physics analysis environment will begin in earnest and will require small-scale production systems no less than an order of magnitude smaller than those used during the data taking period. The scaling factor between the production-prototype systems and the systems used at LHC startup must be kept modest so that the prototype is fully functional, and the full set of problems associated with processing and data handling of the initial LHC data-volumes are adequately understood and handled.

To a first approximation, annual needs for resources in central and regional facilities should remain constant starting two years before full LHC operation and continuing during the data-taking years until the centers have reached their full capacity for support of LHC operation at high luminosity operation. Subsequent requirements for system upgrades and expanded data capacity will need to continue at a lower level.

A.7 US CMS Software and Computing Resource Needs

The computing equipment and personnel requirements which would allow US CMS to be prepared and operated cost effectively are estimated as shown in the table below. This estimate takes into account current and anticipated trends in technology and will be updated regularly. The equipment and personnel shown in the table would have an equivalent value of about 10% of the US CMS project and this fraction is expected to be a more accurate projection than any individual requirement.

	1997	1998	1999	2000	2001	2002	2003	2004	2005
desktop & software (units) (for US physicists in CERN)	7	12	15	16	19	26	36	48	56
simulation facilities (TIPS)	4	18	30	50	80	140	230	390	650
dedicated networks (Mbits/s)	0	2	3	4	11	16	34	96	136
data storage & processing:									
—random access (disk) (Tbytes)	0	0.5	1.3	2.7	5.6	11	30	60	100
—sequential access (Tbytes)	0	1.7	4	8	14	24	150	330	560
—processing (TIPS)	0	1	3	8	20	50	125	250	500
computing professionals (FTE)	2	4	5	6	7	9	10	10	10

Notes:

1. Desktop systems at universities are normally provided by base-program support which is not specific to any experiment. These systems do not appear in the table but will be vital for CMS software development, simulation and physics analysis.

2. US CMS already has a substantial need for simulation facilities in 1997. This results in the exploitation, often parasitically, of existing resources at Fermilab and in US universities. We make maximum use of the base program throughout the construction phase.

3. Some dedicated CMS network links are likely to be required to optimize the support for distributed data analysis. The example in the table assumes only links within the US and gives the sum of the bandwidth of all dedicated links. It is assumed that the majority of CMS traffic within the US will be carried by ESNET and other general-purpose networks and that an adequate CERN-US link will exist.

4. Personnel associated with the operation of computing system are not included and are expected to be provided by the host site.

5. The core computing professionals in the table are expected to be supplemented by a similar number of FTEs from university and laboratory staff. Some of these supplementary FTEs may be provided by physicists with a part-time computing professional role. The activities of all the US computing professionals are summarized below.

Computing Professionals

Three categories of computing professional personnel are essential to the US CMS software and computing project. A breakdown of activities with needs for dedicated US personnel is shown below. The table shows only the US personnel needs; the total CMS effort will be a few times that of the US.

The first category is essential to make CMS software a robust, professional product. A database manager and a software librarian are needed for each area of the US CMS software responsibilities. They should be located at the center of these activities. Computing professionals are also necessary to allow US CMS to contribute to and set directions for core CMS software developments such as object oriented design and programming, and for user interface development.

Activity	People (US)
Detector-specific database structure coordination	3
Software librarians for US CMS detector software	3
Core object-oriented software development team members	2
User-interface (e.g. graphics) development team members	2

The second category involves the development, implementation and support of the data storage and processing system, including the use and development of a distributed object oriented data management system, and the management of the organized production processing (simulation and reconstruction) that is carried out on US facilities. They should be located and supported, at least initially, by the regional center(s).

CMS DBMS development and support	3
Production processing (simulated and real data)	2

The third category provides support mainly aimed at US CMS physicists as part of a coordinated support effort for all CMS. Machine-specific library and environment support should be part of a coordinated worldwide effort to support (at least) the LHC program. It will be vital and inevitable that CMS as a whole will require its software to run on every commercially successful platform, although particular communities within CMS, such as CERN or US CMS may each 'standardize' on one or two platforms. Already CERN is trying to limit its traditional open-ended commitment to support every platform and it has been proposed that, for the immediate future, only Sun and HP will be supported by CERN for LHC experiments. A natural complement to this would be for US CMS to provide the CMS-wide support for one or two out of SGI, DEC and IBM in the immediate future. To be fully effective, this support would have to extend to, for example, helping with real or suspected DEC-specific problems for the whole of CMS.

Machine-specific library and environment support	3
—(Software from CMS, HEP, public domain and vendors)	
Communications and networking support	2
—(including video conferencing and information system)	
	—
TOTAL	20

We will have to utilize personnel from existing programs at Fermilab and a limited number of US CMS universities with 10 FTE's listed in the first table. These personnel do not include many physicists contributing to the US CMS computing effort. It is assumed that the personnel, and indeed the resources needed for US CMS software and computing operations, are supported by the HEP base program of DOE and NSF. As US CMS physicists comprise a significant fraction of all US high energy physicists, then US CMS is an integral part of the US base program, and should be appropriately supported by its funding agencies.

A.8 US CMS Software and Computing Management

The details of US CMS management are provided in the US CMS Project Management Plan. Funding requests and other actions taken in the name of US CMS proceed solely through the executive body of US CMS, the Management Board. Those requests and actions concerning software and computing are made in full consultation with the US Software and Computing Board (see below). The US CMS Software Coordinator, elected by US CMS institutions working on software, is represented on the Management Board on equal footing with all detector subsystems. Nevertheless, software and computing, except for software licenses included in the offline Common Project, slow controls, engineering design, and the level 3 computing farm are considered to be part of US CMS "operations" and not part of US CMS as a construction project. This demarcation is fully consistent with similar projects such as D0, CDF, SDC, GEM, and BaBar.

The overall CMS computing effort is managed by the Software and Computing Technical Board (SCTB) and the Software and Computing Board (SCB). The SCTB coordinates the CMS software and computing project. It is composed of the leaders of the principal components of the software and computing task. The SCB is composed of representatives of groups of universities or major laboratories and acts like an Institution Board of a CMS subdetector. It oversees the SCTB and coordinates software and computing resources. The specific charges of the two boards are as follows. The US members of the SCB and SCTB are shown in Fig. A3. We note that Harvey Newman of Caltech is the current Chair of the SCB. Among the particular roles of the US members are to ensure that the plans for computing developed for US CMS and for CMS as a whole are internally consistent.

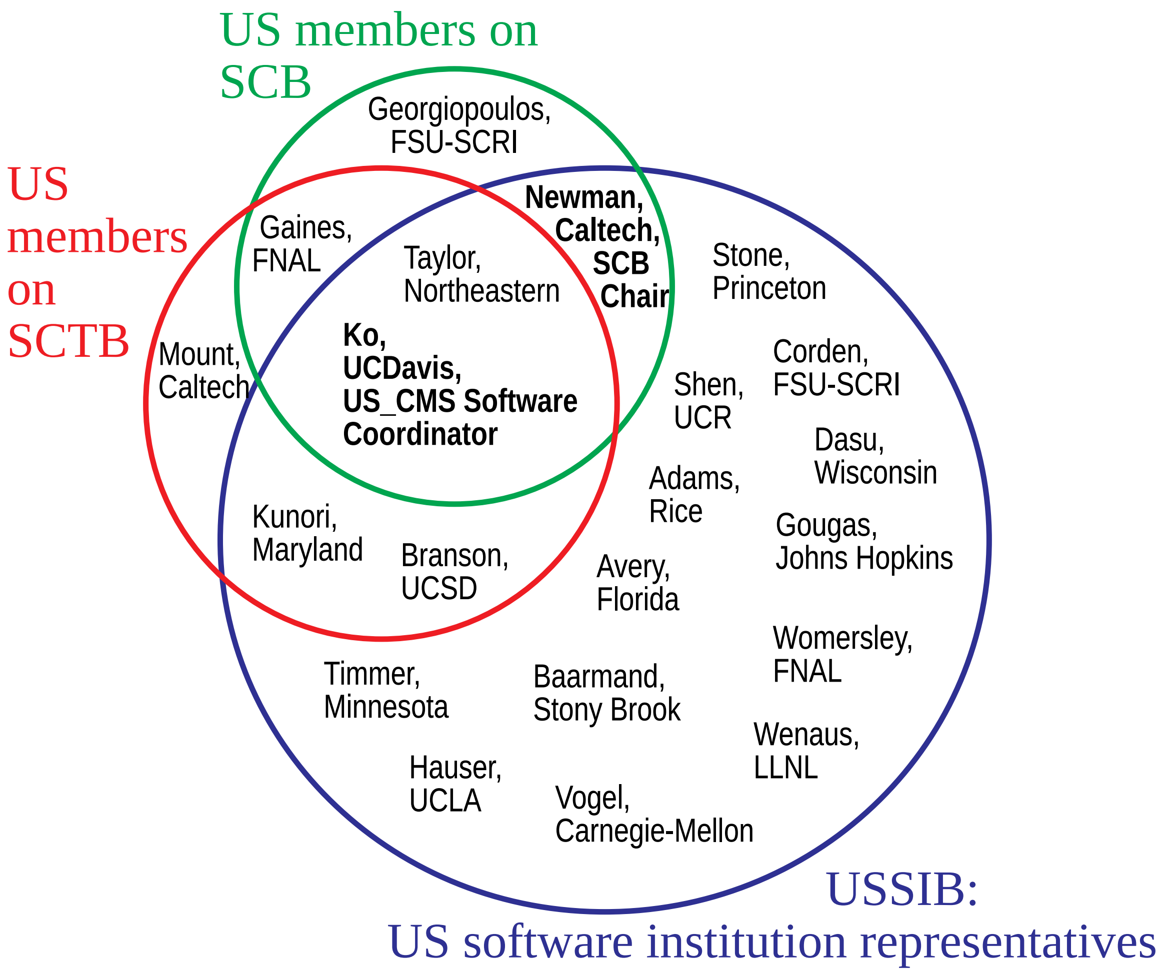


Figure A3: Composition of the US Software and Computing Board.

CMS Software and Computing Board (SCB)

These are the responsibilities of the SCB:

- Overseeing the software and computing task
  - ensure the complete task is done
  - set the scope and scale of the task
  - approve or set major milestones and track progress
- Ensuring that the necessary resources are available and effectively utilized; reviewing, approving and forwarding recommendations for Common Fund projects to the CMS Finance Board and the Management Board
- Coordinating and committing resources including personnel
- Preparing requests to be presented to the CMS Technical Board, the Finance Board and the Management Board
- Negotiating and developing collaborative efforts with CERN and other institutes
- Ensuring coherence of the software and computing environment
  - consistent choice of methods and tools
  - use of standards
- Reviewing and approving proposals from the SCTB; revising in collaboration with the SCTB when needed
- Reviewing and discussing reports from the SCTB at regular intervals.

CMS Software and Computing Technical Board (SCTB)

The SCTB coordinates the CMS software and computing project. It formulates software and computing policy of the collaboration and presents recommendations to the Software and Computing Board (SCB).

The recommendations to the SCB will include resources, technology choices, management structures and procedures, software standards and engineering practices, quality requirements and documentation.

In particular, the SCTB will formulate and update the Computing Model and the Software and Computing Project Management Plan for the collaboration.

The members of the SCTB are appointed by the Software and Computing Project Manager in consultation with the CMS management. One representative per subdetector is nominated by the subdetector project manager in consultation with the Software and Computing Project Manager.

US CMS Software and Computing Coordination

In US CMS governance, all subsystems have subsystem institutional boards comprised of one representative from each participating institute. They in turn elect a subsystem coordinator to the US CMS Management Board.

The Software Coordinator chairs the US Software and Computing Board (USSCB, see Fig. A3), comprised of members of the US Software Institution Board (USSIB) and US members of the SCTB and SCB. In the larger context of CMS, the USSCB reports a coherent view of US computing to the CMS computing project management. With the consent of the US CMS Management Board, the Software Coordinator will then compile, prioritize, and communicate CMS computing requests to all US CMS institutions.

Addendum

The following table listing the US CMS FY 1997 funding request by institution and subsystem was transmitted to DOE on November 11, 1996. The details of the supplemental university travel request summarized in the last column are shown on page 77 in Table 18.

US CMS FY 1997 Funding Request by Institution (K$).

Institution	Subsystem						FY'97 Request		Travel
	EMU	HCAL	TRIDAS	ECAL	Track	PrjMgt	DOE	NSF	DOE
US CMS	**1586.0**	**1861.0**	**659.0**	**571.0**	**423.0**	**301.6**			
DOE	1503.0	1650.0	550.0	514.0	293.0	110.0	**4620.0**		**300.0**
NSF	83.0	211.0	109.0	57.0	130.0	191.6		**781.6**	
Alabama									
Boston		26.0					**26.0**		**4.0**
Brookhaven				27.0			**27.0**		
UC Davis	99.0				177.3		**276.3**		**42.0**
UCLA (DOE)	90.0	20.0	120.0				**230.0**		**21.5**
UCLA (NSF)			5.4					**5.4**	
UC Riverside	21.6						**21.6**		
UC San Diego (DOE)			48.0				**48.0**		**10.0**
UC San Diego (NSF)			45.0					**45.0**	
Caltech				49.5			**49.5**		**20.0**
Carnegie Mellon	97.2						**97.2**		**5.0**
Fairfield		33.0					**33.0**		**5.0**
Fermilab	281.7	645.0	32.0		9.0	110.0	**1077.7**		
FNAL (DOE Reserve)	150.3	225.0	35.0	51.4	29.3		**491.0**		
Florida	162.0						**162.0**		**15.0**
Florida State		80.0					**80.0**		**5.0**
Florida State (SCRI)									**2.0**
Illinois Chicago		58.5						**58.5**	
Iowa		156.0					**156.0**		**14.0**
Iowa State									
Johns Hopkins					117.0			**117.0**	
Livermore									
Los Alamos									
Maryland		160.0					**160.0**		**15.0**
MIT			25.0				**25.0**		**6.0**
Minnesota		70.0		206.1			**276.1**		**22.0**
Mississippi		45.0			13.5		**58.5**		**10.0**
Nebraska			47.7					**47.7**	
SUNY Stony Brook	6.3						**6.3**		
Northeastern	74.7			51.3		191.6		**317.6**	
NEU (NSF Reserve)	8.3	21.1	10.9	5.7	13.0			**59.0**	
Northwestern					63.9		**63.9**		**10.0**
Notre Dame		77.4						**77.4**	
Ohio State	283.5						**283.5**		**10.0**
Princeton				180.0			**180.0**		**15.0**
Purdue D	45.9						**45.9**		**10.0**
Purdue G		50.0					**50.0**		**7.0**
Rice	27.0		40.0				**67.0**		**12.5**
Rochester		115.0					**115.0**		**11.0**
UT Dallas									
Texas Tech		25.0					**25.0**		**7.0**
Virginia Tech		54.0						**54.0**	
Wisconsin	238.5		250.0				**488.5**		**21.0**

[This printing includes corrections received through November 15, 1996.]